



## **Flight Dynamics Analysis Branch End of Fiscal Year 2000 Report**

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## **Abstract**

This report summarizes the major activities and accomplishments carried out by the Flight Dynamics Analysis Branch (FDAB), Code 572, in support of flight projects and technology development initiatives in Fiscal Year (FY) 2000. The report is intended to serve as a summary of the type of support carried out by the FDAB, as well as a concise reference of key accomplishments and mission experience derived from the various mission support roles. The primary focus of the FDAB is to provide expertise in the disciplines of flight dynamics, spacecraft trajectory, attitude analysis, and attitude determination and control. The FDAB currently provides support for missions and technology development projects involving NASA, government, university, and private industry.



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## **1.0 Introduction**

The Guidance, Navigation and Control Center (GNCC) at the Goddard Space Flight Center (GSFC) provides the skills, vision and leadership in guidance, navigation and control (GN&C) systems, engineering, operations and mission analysis to enable revolutionary Earth and Space Science discovery. The scope of technical disciplines encompassed by the GNCC is broad and includes all aspects of flight dynamics, propulsion, flight mechanics, guidance, navigation and control engineering for space systems, experiments, and sub-orbital missions. The range of products and services is also broad and requires expertise in skill areas such as advanced component design, control system architecture, propulsion design, trajectory analysis, autonomy and mission design.

Within the GNCC, the Flight Dynamics Analysis Branch (FDAB), Code 572, is responsible for providing Guidance, Navigation and Control analytic expertise for trajectory and attitude systems. This includes dynamics and control analyses and simulations of space vehicles. The Branch creates and maintains state-of-the-art analysis tools for mission design, trajectory optimization, orbit analysis, navigation, attitude determination, and controls analysis. The Branch also provides the expertise to support a wide range of flight dynamics services such as mission design, on-orbit sensor calibration, and launch/early orbit operations. The FDAB also maintains an active technology development program, with special emphasis on developing new techniques and algorithms for autonomous orbit/attitude systems and advanced approaches for trajectory design. Specific areas of expertise resident in the FDAB are:

- Attitude and trajectory analysis and control design
- Control/Structure interaction analysis
- Mission (attitude & trajectory) planning
- Estimation techniques
- Vehicle autonomy
- Constellation analysis
- Flight Dynamics model development

This document summarizes the major activities and accomplishments performed by the FDAB in support of flight projects and technology development initiatives in Fiscal Year (FY) 2000. The document is intended to serve as both an introduction to the type of support carried out by the FDAB, as well as a concise reference summarizing key analysis results and mission experience derived from the various mission support roles assumed over the past year. The FDAB staff that are involved in the various analysis activities within the branch prepared this document. Where applicable, these staff members are identified and can be contacted for additional information on their respective projects.

Among the major highlights by engineers in the FDAB during FY2000 are:

- Controlled reentry planning and operations for the Compton Gamma Ray Observatory (CGRO)
- Successful launch and early operations support for the Terra and GOES-L missions
- Design and implementation of the control system for Triana
- Successful mission design and attitude control system analysis support to numerous mission concept studies such as GPM, MMS, Constellation X and Nexus
- First operational use of the Tracking Data Relay Satellite System (TDRSS) Onboard Navigation System software in support of routine Terra operations
- GSFC Software of the Year award given to the Global Positioning System (GPS) Enhanced Orbit Determination (GEODE) software (runner-up for the NASA Software of the Year award)
- Delivery of GEODE release (V5) supporting relative navigation in Highly Elliptical Orbit (HEO) and Geosynchronous Earth Orbit (GEO) missions, and relative navigation
- GEODE initial integration with PiVoT GPS Receiver & ITT Low Power Transceiver
- More than a dozen technical papers and journal articles as well as active participation at national and international GN&C/Flight Dynamics conferences
- Initial "operational" configuration of the Flight Dynamics Lab completed

## **2.0 Flight Project Support**

This section summarizes FDAB support to Goddard flight projects during FY00. For purposes of this report, these projects are classified as:

- *Development Missions:* Approved missions under development.
- *Operational Missions:* Missions that were in-flight in FY00. This includes missions that were in the final stages of development and were successfully launched in FY00 (e.g. Terra).

Support to future mission concept studies and proposal support for missions seeking project approval are covered in section 3.

### **2.1 Development Missions**

#### **2.1.1 Earth Observing-1 (EO-1) (planned launch 11/2000)**

The Earth Observing -1 mission (EO-1) is scheduled for launch in the later half of November, 2000. This Sun-synchronous mission will fly in formation with the Landsat-7 spacecraft during its nominal one year lifetime. The formation will consist of EO-1 remaining one minute (+/- 6 seconds) behind Landsat-7 in Mean Local Time at the descending node. Other orbital parameters are to remain essentially the same as those of Landsat-7. EO-1 contains three primary instruments: the Advanced Land Imager (ALI), the Atmospheric Corrector (AC) and Hyperion. The ALI, built by the Massachusetts Institute of Technology/Lincoln Laboratories (MIT/LL), is the next generation of Earth Imager that will continue the work carried on through 25 years of NASA's Landsat programs. To validate the quality of the ALI, the mission's main goal is to compare 200 co-fly scenes taken by both EO-1 and Landsat-7. Approximately 1000 co-fly scenes will be taken to achieve the best 200 scenes. In addition to the instruments mentioned, EO-1 is a space technology mission featuring a total of 10 different space related technologies.

The Flight Dynamics Analysis Branch (FDAB) has taken the lead in preparing the tools and training personnel to provide Flight Dynamics support to EO-1 during EO-1 Launch & Early Orbit (L&EO) and Normal Operations. For L&EO, the team will consist of members of the FDAB, the EO-1 Flight Operations Team (FOT), the Flight Dynamics Facility and AI-Solutions, Inc. Support from the L&EO flight dynamics team will continue until approximately Launch + 45 days. All Flight Dynamics support after the first 8-10 hours of the mission will be performed in the EO-1 Mission Operations Center (MOC). The institutional Flight Dynamics Facility will provide some early orbit support, mostly involving TDRS.

The EO-1 Flight Dynamics Support Subsystem (FDSS) will reside on redundant HP Workstations and PC/NTs in the MOC. The four major processes for this support include: orbit determination, orbit maneuver control, orbit & attitude product generation and attitude support, including planning instrument calibrations. All are supported using Commercial Off-the-Shelf (COTS) based software to reduce costs. The L&EO period nominally includes 8 orbit maneuvers taking 17 days to phase EO-1 into its required orbit with respect to Landsat-7. Between these maneuvers, sensor and gyro calibrations will be performed.

Tracking data for EO-1 is nominally from the Global Positioning System (GPS) with S-Band tracking used for validation of GPS and backup. After supporting EO-1 for several months using ground based Formation Flying calculations for orbit maneuvers, the onboard Enhanced Formation Flying algorithm will become prime with the ground software used as a validation tool and a backup.

The FDSS will provide approximately 25 orbit and attitude products weekly to the EO-1 Principal Investigators and the Mission Operations Planning and Scheduling System (MOPSS) personnel at GSFC who support the EO-1 Mission Science Office.

*Note: See section 4.3.1 for a description of the EO-1 formation flying experiment, and section 4.2.4 for a description of FDAB involvement with the EO-1 GPS package.*

[Technical contacts: Robert L. DeFazio, Richard J. Luquette, Chad Mendelsohn]

### **2.1.2 Microwave Anisotropy Probe (MAP) (planned launch 7/2001)**

Microwave Anisotropy Probe (MAP) is a MIDEX-class mission produced in partnership between GSFC and Princeton University. The primary objective is to measure temperature fluctuations and to produce a high sensitive and spatial resolution map of the cosmic microwave background radiation over the entire sky. There is only one instrument on the spacecraft. The MAP will be placed in a Lissajous orbit about the Sun-Earth L2 Lagrange point 1.5 million kilometers from Earth.

FY 2000 has been a very productive and busy year for the MAP team as we are preparing for a launch in the second quarter of 2001. The MAP spacecraft launch has been manifested for no earlier than April 18, 2001. Flight Dynamics Analysis Branch members of the Attitude Control System (ACS), and flight dynamics teams have successfully completed a number of important milestones during this year.

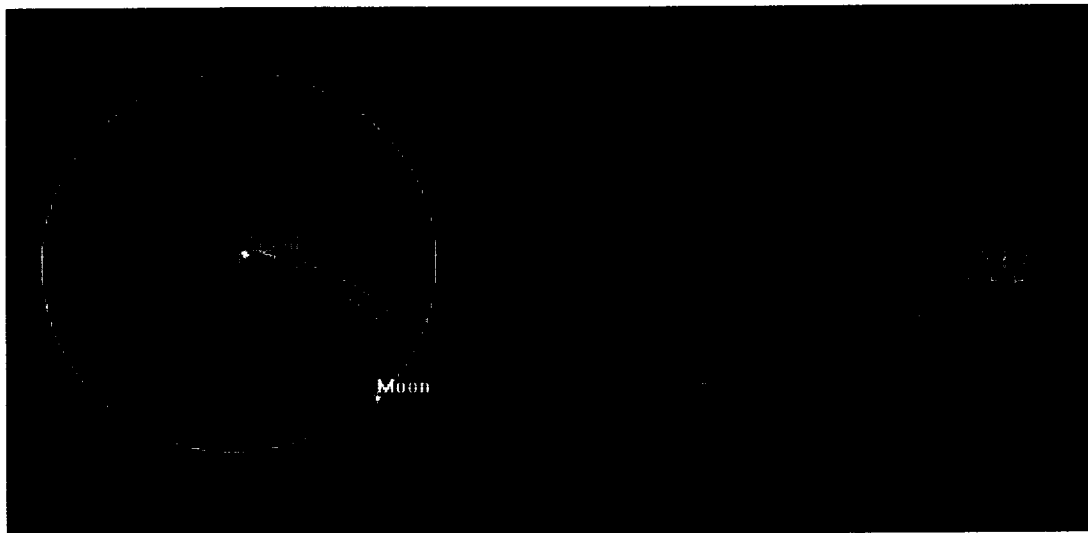
In the trajectory design area, several major reviews were held during this fiscal year to present the status of the trajectory design, maneuver operations and navigation support. Several independent (outside GSFC) flight dynamics experts supported the reviews. These included trajectory peer reviews in December 1999 and September 2000, in addition to a trajectory review conducted as part of the Flight Operations Review in April 2000. At the beginning of January 2000, a tiger team, consisting of representatives from all areas of the MAP project, was formed to address the action items from the December 1999 Trajectory Design Review. Once the tiger team identified all the work needed to be done in the Trajectory Design and Maneuver Operations areas, it evolved into the Maneuver Operations Team. The team currently consists of representatives from Trajectory Design, ACS, Propulsion, Flight Software, S/C controllers, and Navigation.

The Maneuver Ops Team was formed to address the problem of planning, executing, and verifying all maneuvers. The Maneuver Team has generated information flow diagrams and has developed processes to plan, execute, and verify maneuvers. This entire process has been demonstrated during several maneuver simulations, and is currently being refined and updated. The Maneuver team has also been instrumental in setting up for these simulations, evaluating anomalies, and verifying the performance of the maneuvers. We have also identified interfaces between subsystems, the software required to plan the maneuver, and the data and file formats. Interface Control Documents (ICDs) are currently under development and various procedures have been written and implemented in support of the simulations. To increase the accuracy of the simulations, we added a propulsion blowdown model to the Hybrid Dynamic Simulator (HDS) and to the ACS HiFi simulation to properly model the effects of thruster firings on the fuel mass. In addition, fuel budgets were produced many times in support of many reviews during the year. The team has already supported several simulations and will continue to support simulations on a monthly basis.

The MAP team has also completed a significant amount of analysis work. In particular, we have completed and delivered most of the nominal trajectories for the prospective launch months of April, May, June, and July to Boeing. We have completed and documented a number of contingency analyses as well as other trajectory analysis requested by the Trajectory Peer review panel from the December 1999 review and by the MAP project. We have completed the following contingency analysis: Using Mid Course Correction (MCC) delta V to remove L2 lunar Shadows, lunar shadow avoidance at L2, missed first perigee (P1) maneuver, strategy to move perigee maneuvers into a station contact and splitting perigee maneuvers to mention a few. In addition, we completed an orbit determination covariance analysis for the phasing loops and L2 phases which was used to derive the orbit determination requirements and tracking requirements for maneuver calibration and planning. Figure 2-1 shows the MAP trajectory.

Moreover, the trajectory team also built an analytic model for the phasing loops that determines delta-V distribution across perigee maneuvers to achieve the proper timing and energy. We also performed analysis to design the MAP trajectories with an opening Lissajous and to determine the Lissajous amplitude to meet MAP constraints. In addition to all the analysis mentioned above, the trajectory team performed a parametric study and later a Monte Carlo analysis to investigate the launch vehicle dispersions in order to guarantee that trajectories that satisfy all mission requirements are available for all dispersions and within the fuel budget. We also developed a Matlab script as an automated way to evaluate the maneuver execution errors.

Finally the MAP team has supported a large numbers of MAP reviews such as the MAP L-1 year review, the Flight Operations Review, Environmental Review, and the Red Team Review.



**Figure 2-1. Sample of the MAP 3-loop trajectory**

The ACS team has also had a busy and productive year. Spacecraft integration and testing (I&T) started in earnest for us, as did the mission simulations. We continued updating and refining our design as test results and updated mass properties became available.

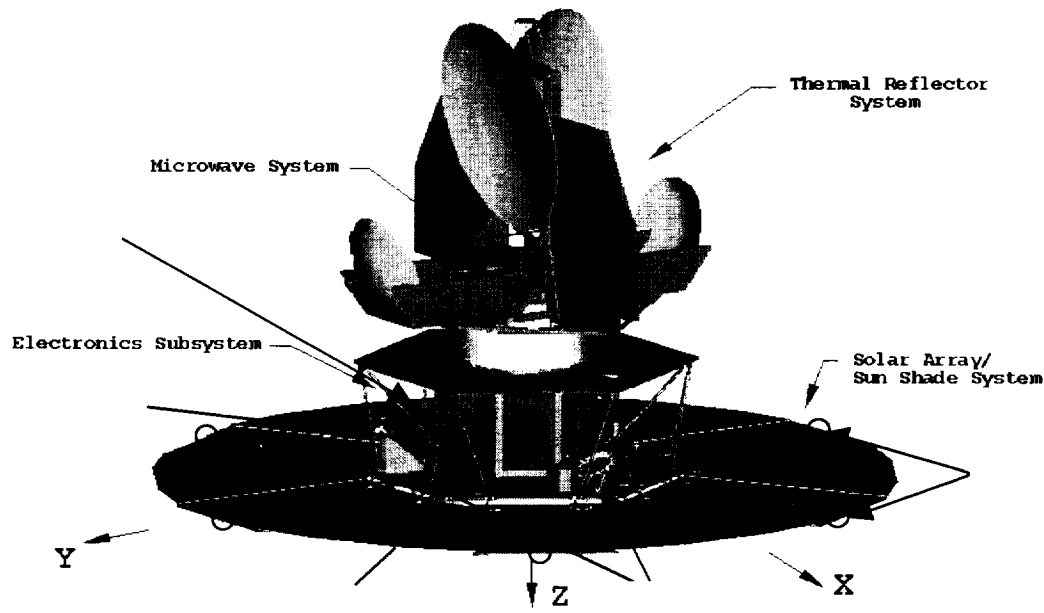
Much of the I&T was at the subsystem or spacecraft level. Some components were reintegrated and retested, but the main goal was to get the ACS subsystem ready for the Comprehensive Performance Test (CPT). In February, we ran a series of functional tests on the spacecraft. These tests ensure that the open-loop commanding of the spacecraft and the stimulating of the sensors produces the desired results. We tested such components as the Coarse Sun Sensors (CSS), Reaction Wheels Assemblies (RWA), and the Digital Sun Sensor (DSS), in addition to testing the Kalman filter (with the Autonomous Star Tracker (AST) and star tracker stimulus), Observing Mode, Delta V Mode, Sun Acquisition Mode, and our Safehold modes.

April 2000 brought more functional testing on the spacecraft, the AST standalone functional and thermal vac tests, and four days of CPT dry run testing. This testing culminated with 8 days of continuous testing on the spacecraft during CPT #1. The ACS team provided 24-hour coverage during the week of testing.

In addition to spacecraft testing, there was also operations testing in the form of mission simulations. We did a launch simulation in the MAP SMOC with the spacecraft in the spring, and that transitioned into an early ops sim on FlatSat. The mission sims that included maneuvers, and involved all the subsystems and spacecraft controllers, started in June. These simulations were a combination of nominal and contingency scenarios. The ACS team and the Maneuver team were involved in setting up for the simulations, supporting the sims while they were running, and evaluating and recovering from any anomalies encountered.

The ACS team also performed other analysis and support duties during the year. In case the current baselined star trackers failed during testing, the MAP project decided to buy two Ball star trackers. During the past year, team members refined the software requirements, added a star catalog, coded software, modified a version of the HDS, and got ready for software testing for the Ball tracker if it was needed.

We received new mass properties in Spring 2000 and noticed that the center of mass was out of specifications. This caused one of our backup thruster modes to be unstable. The fix to this problem included software changes, and, more significantly, the addition of a bend to two of the thrusters to regain a backup mode. Also, we recalculated the control gains to give us the desired stability margins and performance with the new inertias. Figure 2-2 shows the spacecraft.



**Figure 2-2. MAP—Deployed Configuration**

Other work performed in FY00 included:

- Helped deliver flight software (FSW) builds.
- FSW acceptance testing, regression testing
- Failure Detection and Correction/Telemetry Statistics Monitor/Relative Time Sequence updates and modifications, based on testing.
- Supported Launch-1 Year Review.
- Supported Pre-Environmental Review.
- Component electrical integration and testing.
- Updated and corrected alignment document.
- Electro-Static Discharge training for team members who are going to be working near the spacecraft.
- Optical alignment shots during Aug. and Sept to check pre-thermal-vacuum component alignments.
- Started work on ops contingency flowcharts.

The public MAP home page is <http://map.gsfc.nasa.gov>. You can find pictures of the spacecraft, the instrument, and some science background and procedures.

[Technical Contacts: [Osvaldo Cuevas](#), [Steve Andrews](#)]

### **2.1.3 EOS AQUA Mission (planned launch 7/2001)**

During FY00, FDAB engineers finalized the FDS (Flight Dynamics System) segment of the Ground System Requirements Document (GSRD) and boarded the Interface Control Documents (ICDs) for the FDS to Flight Operations Team (FOT), FDS to Distributed Active Archive Center (DAAC), and FDS to EOS Mission Operations System (EMOS) documents. The team also continued with orbit determination error and tracking requirements analyses, launch window analysis, and maneuver analysis. A new ascent scenario was developed and nominal launch parameters were adjusted to reduce the inclination adjust maneuver frequency and eliminate the possibility of 3-sigma launch dispersions resulting in undesirable maneuvers. The FDAB continued working with the software development team on the FDS operations concept and system specifications. An attitude and maneuver telemetry mnemonic list based on the Aqua Project Data Base was delivered and the team supported Project-level meetings with the spacecraft vendor, Principal Investigators (PIs), and other Goddard mission interfaces. Finally, the FDAB worked with Project personnel to define FDS participation in mission/spacecraft simulations and delivered FDS planning products used by the Mission Planning Team to

develop nominal mission timeline for use by other AQUA mission groups. Installation of FDS hardware in the EOS mission operations center and testing the FDS software was initiated.

[Technical contact: David Tracewell]

#### **2.1.4 TRIANA (planned launch 4/2002)**

The Triana ACS team completed all preliminary design reviews last year (May '99–July '99). The onboard control system utilizes five distinct controllers to support orbit maintenance, safing and science operations. One innovative feature is the gyroless Safehold control scheme, developed by Roger Chen of K&D, which allows Triana to control rates based on the behavior of the reaction wheels. In September the FDAB engineers held a second peer review to cover the flexible mode stability issues that were not addressed in the May 1999 review.

This year, the FDAB ACS analysis team worked closely with the software development and test teams to implement the Triana control system. We have completed the initial ACS subsystem, taking our controller designs from a mathematical simulation to a real time flight system; working against an incredibly challenging schedule.

This fall, all of the ACS team (hardware, software, analysis) will be supporting the spacecraft integration and test phase of the mission. During this activity, we will integrate our ACS subsystem with the main spacecraft bus and perform a wide range of tests to validate the flight system.

FDAB orbit analysis engineers made some significant strides with the Generator software used for trajectory design. Also, they've faced a lot of challenges with the intricate "launch a second stage from the shuttle" plan and the commercial, yet to be built, ground system.

Purdue University's Generator software will be used to generate the nominal Triana trajectories to the L1 Sun-Earth libration point which require planning the Triana STS deployment and Gyroscopic Upper Stage (GUS) burn. The upper stage which will be used to place Triana on an L1 trajectory from a low Earth STS deployment orbit has dispersions that are considerably larger than those used for similar missions in the past. GSFC's Swingby software will be used to plan the trajectory correction maneuvers. The Goddard Trajectory Determination System (GTDS) software will be used to perform orbit determination. Orbit determination will be performed using tracking data received from the Deep Space Network (DSN) and the Universal Space Network (USN). Prior to the Triana launch the USN's tracking data will be evaluated and certified by CSOC personnel.

Figure 2-3 shows the Triana spacecraft. For complete details about the TRIANA mission refer to <http:// triana.gsfc.nasa.gov/home>



**Figure 2-3. Triana Spacecraft**

#### **2.1.5 EOS AURA (planned launch 6/2003)**

The Aura Mission (formerly called Chemistry) was established in December 1991 and will be launched in June 2003 on a Delta 7920 rocket from the Western Test Range. The operational mission period is planned for six years. The Aura Mission is composed of four complementary instruments on the EOS Common Spacecraft.

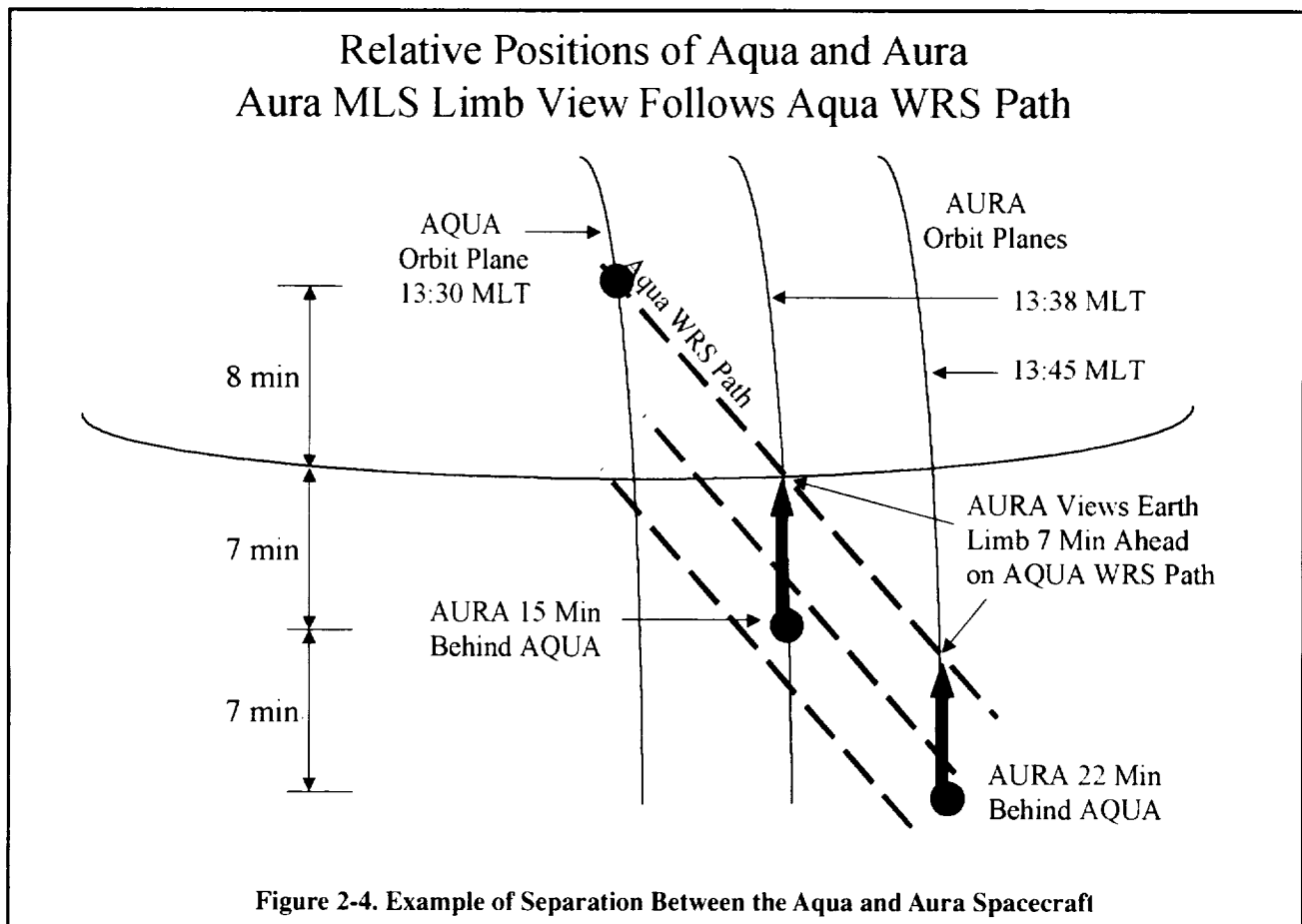
The EOS Aura mission's major science objective is the study of the chemical interactions and climate change in the Earth's atmosphere, focusing on the upper troposphere and lower stratosphere. The Aura spacecraft is a 3-axis stabilized vehicle that will operate in a near-circular, Sun-synchronous polar orbit at an altitude of approximately 705 km, with ascending nodal crossings at approximately 1:45 PM spacecraft mean local time.

Pre-launch flight dynamics services include mission design analysis, trajectory analysis, sensor analysis, and operations planning. Operational flight dynamics support services include orbit and attitude determination validation, anomaly resolution, maneuver planning and support, sensor calibration, and generation of planning and scheduling data products.

During FY2000 FDAB provided the following support: Completed analysis on orbital insertion options, launch window definition, mission phasing strategy, spacecraft reentry prediction, and station coverage; made recommendations on how to get the ascending node crossing time off the uplink data, and what information can be delivered on South Pole coverage; submitted review inputs to the Operations Concept Document and the Mission Specific Requirements Document (MSRD); presented the flight dynamics support briefing to the Aura instruments Mission Operations Working Group (MOWG) at TRW, California; held a preliminary discussion with TRW flight dynamics personnel; and gave a briefing to the Project Scientist on flight dynamics scenarios.

The Aura spacecraft Microwave Limb Sounder (MLS) is a forward-looking instrument that views the Earth's limb. The desire is to coordinate observations between the Aqua spacecraft instruments, looking in the nadir direction, and the Aura MLS. The idea is for Aura to view a point on the Earth's limb a short time after Aqua has flown directly over that point. Aqua will be flying on the World Reference System (WRS). Figure 2-4 shows an example of separation between Aqua and Aura.

For project information about the Aura mission, please refer to <http://eos-aura.gsfc.nasa.gov/>



[Technical contact: [Felipe Flores-Amaya](#)]

### **2.1.6 Space Technology (ST)-5 (planned launch 2003)**

Space Technology-5 (ST-5) is the fifth mission in NASA's New Millennium program and is planned for launch in 2003. The purpose of the mission is to validate methods of operating several highly miniaturized autonomous spacecraft as a system, and test technologies in the harsh space environment near the boundary of Earth's magnetosphere. The program's goal is to dramatically reduce the weight, size and costs of missions while increasing their science capabilities.

The GNCC is responsible for the constellation mission design and the Attitude Control System (ACS) design. A single miniature cold gas thruster will be used for both attitude control and orbit adjustments. Each of the three ST-5 spacecraft is spin-stabilized. A Sun sensor and magnetometer will allow for attitude estimation. Passive nutation damping will be provided by a fluid-filled ring nutation damper. Limitations imposed by the spacecraft onboard computer make it necessary to design computationally simple attitude control algorithms based on Rhumb line spin axis precession and to depend on passive nutation control.

[Technical contacts: Marco Concha, Jim Morrissey, Mark Woodard]

### **2.1.7 Geostationary Operational Environmental Satellite (GOES)-(N-Q)**

Work has begun on planning the next series of NOAA geostationary spacecraft, GOES-(N-Q). The major procedural difference in this new series from a flight dynamics perspective is that the spacecraft builder, Hughes Space and Communications Company, will perform the Launch and Orbit Raising (LOR) activities during the first 20-30 days of the mission. The NASA/GSFC Flight Dynamics Team will only provide a consulting role for the pre-launch activities plus the LOR. Following LOR, the NASA GOES FD Team will have a more active role during the spacecraft Post Launch Testing (PLT) period before handover to NOAA.

The NASA GOES FD Team has participated throughout the past year in reviews of the GOES-(N-Q) Detailed Mission Requirements, by attending major reviews of the program and by developing a plan to update flight dynamics tools for future GOES-(N-Q) consulting activities. Despite not having the leading flight dynamics role in these missions, the NASA FD Team will be ready to provide any support that will help to insure the success of this program.

[Technical contact: Robert L. DeFazio]

### **2.1.8 Balloon Program**

#### *Infocus*

The InFocus telescope is a nine-meter long X-ray telescope being developed at GSFC for flight on high altitude (40 km) stratospheric balloons. Part of the InFocus development effort is improving pointing performance. An eventual goal is to point this telescope to inertial targets within an arc-second. Historically, this accuracy has not been achieved on balloon payloads due to the level of torque disturbances, which are significantly higher than those found in an orbiting environment. Several avenues are being pursued with analysis, modeling, and simulations in concert with ground testing and flight measurements.

An Infocus Balloon test flight was instrumented for making in-flight observations of the disturbances train dynamics. The flight was launched in August from Palestine, Texas, and measurements were made for several hours. The test flight did not carry the entire telescope. A second balloon flight, scheduled for June, 2001, will carry the complete Infocus telescope. The telescope will be pointed using a standard azimuth-elevation pointing control system with the goal of achieving pointing performance of several arc-minutes. A third planned flight of the InFocus Telescope changes the pointing scheme entirely. Whereas most pointed balloon instruments use the azimuth/elevation approach, the InFocus engineering team has been developing a mechanical load-carrying interface between the pointed and non-pointed portions of the gondola payload made up of a sealed cup/ball bearing continuously charged with oil. When uncaged at float altitude, the low-friction, three-degree-of-freedom bearing will allow the pointed section, consisting of the telescope and support subsystems, to be controlled with the same attitude control components found on satellites, e.g., reaction wheels, magnetic torquers, star tracker and gyros. The goal is to achieve arc-second accuracy for multiple targets. Analysis, modeling, and simulation are now underway to specify and size the critical control elements in the system.



A key problem to improvement of balloon pointing accuracy is the understanding of the disturbances from the several-hundreds-of-feet-long load train connecting the balloon and gondola. The train dynamics has been under study in the past year not only for the InFocus mission but for the benefit of other experiments in the balloon program as well. The train includes the recovery parachute immediately below the balloon, and several multi-cable sections, the largest of which is a sixty-five foot-long multi-cable ladder between the bottom of the parachute and the top of the gondola. Disturbances about the vertical axis are particularly acute because the torsional rigidity is very weak. Disturbances originating from balloon oscillations, rotations, altitude changes, and aerodynamics propagate through the train to disturb the azimuth pointing control. Attempts to isolate gondolas from this effect, usually by coupled bearings below the ladder, are compromised by non-linear friction and an occasional need to use a bearing motor to transfer accumulated angular momentum from the gondola into the train itself.

In the past, for practical reasons, measurements of these disturbances have been hard to make. This year the sixty-five foot long ladder section of the balloon train was suspended at GSFC from the ceiling of a high bay and excited under simulated load. Laser optical measurements of azimuth angular motion were made. Additionally, on the InFocus Test Flight, sensors were included to make in-flight measurements of the attitude motion. The sensors included several magnetometers on the train/gondola plus a gyro IMU on the gondola itself. An azimuth reaction wheel was also flown and used to excite the gondola/train motion.

A possible byproduct of this effort will be recommendations to the standard design of the balloon train for all balloon payloads with an aim of lessening the torque disturbance environment from the train. Depending on these results there could be a test flight to qualify the design. There is also the possibility of developing small "piggyback" self-contained instrumentation packs to be placed on many balloon flights in order to establish a database on the train dynamics.

The FDAB is also studying a proposal for an additional flight prior to the InFocus flight. The purpose of the additional flight would be to demonstrate the feasibility of arc second pointing capability on balloon payloads. This mission would develop a gimballed pointing system to carry an existing solar telescope. The gimbal load bearings would be continuously rotating to lessen and linearize the unwanted bearing friction. The pointing would incorporate arc-second accuracy attitude sensors and pointed finely in two degree-of-freedom at a high signal-to-noise ratio source such as the Sun.

[Technical contact: David Olney]

## **2.2 Operational Missions**

### **2.2.1 EOS Earth Observing System Terra**

The EOS Terra spacecraft, formerly known as EOS AM-1, launched from Vandenberg AFB on December 18, 1999, at 18:57:36 Z, within 20 seconds of the end of the window. Terra was placed into a nominal injection orbit of 655 x 695 km by the Atlas IIAS launch vehicle. FDAB analysts were tasked with planning the maneuvers to place Terra into its final mission orbit, as well as monitoring and calibrating the attitude control system. After successfully executing pulses of each of the thrusters and an 11 sec calibration burn, the first of four planned ascent maneuvers was set for January 11. After only 66.7 sec of the planned 516 sec duration, however, the burn was aborted due to a high pitch rate. Careful investigation by the spacecraft engineers revealed the cause as a combination of impingement of the thruster plume on the solar array and poor knowledge of the location of the spacecraft center of mass in the onboard attitude controller. These problems were addressed by parking the solar array at a favorable angle for minimizing impingement during future maneuvers and by updating the thruster pairing matrix onboard. The GN&C maneuver team replanned the ascent using shorter maneuvers and was able to place the spacecraft on orbit on February 23, 2000.

Due to the extended amount of time that Terra spent in the injection orbit while awaiting anomaly resolution, the orbit inclination drifted farther than planned. Two inclination maneuvers were performed to bring the mean local time of descending node back within the 10:30 +/- 15 min control box. The mean local time is now decreasing towards 10:15 am. Maneuvers will have to be performed in about 3 years to turn the drift back around towards 10:45 again. The maneuvers executed are shown in table 2-1 below:

**Table 2-1. Terra Actual Maneuver Sequence**

| <b>Maneuver</b>     | <b>Date</b> | <b>Duration<br/>(sec)</b> | <b>Planned<br/>Delta-V<br/>(m/s)</b> | <b>Achieved<br/>Delta-V<br/>(m/s)</b> | <b>Planned<br/>Thrust<br/>Factor</b> | <b>Achieved<br/>Thrust<br/>Factor</b> |
|---------------------|-------------|---------------------------|--------------------------------------|---------------------------------------|--------------------------------------|---------------------------------------|
| Hardware Test Fire  | 1/4/00      | 0.496                     | 0.0051                               | 0.0038                                | 100.00%                              | 73.37%                                |
| Hardware Test Fire  | 1/15/00     | 0.496                     | 0.0052                               | 0.0042                                | 100.00%                              | 80.89%                                |
| Engineering Burn    | 1/10/00     | 11.000                    | 0.1166                               | 0.1097                                | 100.00%                              | 94.10%                                |
| Delta-V 1 (aborted) | 1/11/00     | 66.560                    | 0.6902                               | 0.6678                                | 99.00%                               | 95.79%                                |
| Test Burns          | 2/2/00      | 40.000                    | 0.4109                               | 0.3932                                | 99.00%                               | 94.76%                                |
| Boost Burn 1        | 2/10/00     | 60.000                    | 0.5937                               | 0.5862                                | 96.00%                               | 94.80%                                |
| Boost Burn 2        | 2/12/00     | 150.000                   | 1.4782                               | 1.4488                                | 97.00%                               | 95.07%                                |
| Boost Burn 3        | 2/14/00     | 320.000                   | 2.8251                               | 2.8286                                | 95.00%                               | 95.12%                                |
| Boost Burn 4        | 2/16/00     | 320.000                   | 2.9186                               | 2.9275                                | 95.00%                               | 95.29%                                |
| Boost Burn 5        | 2/18/00     | 320.000                   | 2.8338                               | 2.8408                                | 95.00%                               | 95.23%                                |
| Boost Burn 6        | 2/20/00     | 320.000                   | 2.7630                               | 2.7592                                | 95.20%                               | 95.07%                                |
| Boost Burn 7        | 2/22/00     | 280.000                   | 2.3492                               | 2.3553                                | 95.10%                               | 95.35%                                |
| Boost Burn 8        | 2/23/00     | 110.000                   | 0.9089                               | 0.9069                                | 95.10%                               | 94.89%                                |
| GroundTrack 1       | 3/14/00     | 21.376                    | 0.1774                               | 0.1762                                | 95.00%                               | 94.40%                                |
| GroundTrack 2       | 4/12/00     | 26                        | 0.2177                               | 0.2178                                | 94.50%                               | 94.55%                                |
| Inclination 1       | 4/27/00     | 320                       | 2.5970                               | 2.6103                                | 95.00%                               | 95.52%                                |
| Inclination 2       | 4/28/00     | 320                       | 2.5501                               | 2.5478                                | 95.50%                               | 95.42%                                |

The FDAB also planned several attitude slews needed to calibrate the attitude sensors and science instruments. These included the Moderate Resolution Imaging Spectroradiometer (MODIS) roll slews on 3/24/00, MODIS yaw slews on 4/25/00 and 4/26/00, and attitude calibration slews on 3/16/00 and 4/13/00. The calibrated IRU and star tracker provide RSS attitude estimation errors of <3 arc-sec.

The control of the Terra attitude and maneuver functions, in addition to the entire Flight Dynamics ground system which produces the science and housekeeping products, was handed over to the control of the Terra Flight Operations Team on May 1, 2000.

*Note: See section 4.2.1 for a description of the TDRS Onboard Navigation System (TONS) used for Terra.*

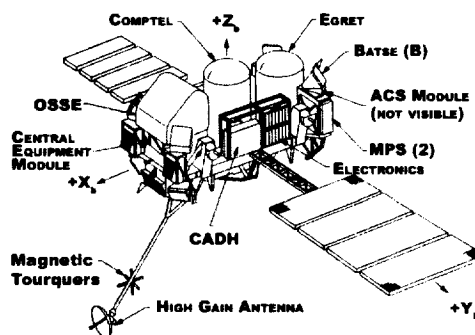
[Technical contact: [Lauri Newman](#)]

### **2.2.2 GOES-L Launch Support**

The GOES-L spacecraft, the fourth of a five spacecraft series of the National Oceanic and Atmospheric Administration (NOAA) geostationary weather satellites, was launched on May 3, 2000 aboard an Atlas-IIa rocket from the Kennedy Space Center. After being delayed for over a year due to a Centaur rocket motor problem, the launch was achieved with near perfection. The NASA/Goddard Flight Dynamics Team performed the Launch and Early Orbit flight dynamics operations from both the NOAA Spacecraft Operations Control Center in Suitland, Maryland and the NASA/GSFC Flight Dynamics Facility in Greenbelt, Maryland. A well-prepared team of flight dynamics personnel consisting of NASA, Computer Sciences, Honeywell and Space System / Loral members supported the NASA GOES Project and the GOES Mission Operations Support Team (MOST) from launch through the arrival of GOES-L (eventually renamed GOES-11) at its initial geostationary orbit location. The support consisted of 9 orbit maneuvers and numerous attitude maneuvers, orbit determinations, acquisition data generations and gyro calibrations. These were achieved with great success and met all the stated requirements of the GOES Project. The final spacecraft in this series is scheduled for launch in mid-July, 2001.

### 2.2.3 The Re-Entry of the Compton Gamma Ray Observatory

On June 4<sup>th</sup>, 2000, the Compton Gamma Ray Observatory (CGRO) successfully entered the Earth's atmosphere over the targeted Pacific Ocean. This is the first time NASA has conducted a controlled re-entry of an unmanned spacecraft from Low Earth Orbit (LEO). The criticality of this GN&C intensive operation was enhanced due to the large mass of the spacecraft, 14,000 kg (15.5 tons) post final burn, and the loss of two of the four orbit control thrusters soon after launch in 1991. Over the spacecraft's nine year lifetime, two orbit re-boosts were done to raise the operational orbit of the spacecraft and extend its science lifetime. During the beginning of the first re-boost effort, one of the redundant attitude control thrusters had a major drop in performance. This thruster had since recovered to near nominal performance and was considered fully operational during the re-entry. Figure 2-5 shows the spacecraft.



**Figure 2-5. The Compton Gamma Ray Observatory**

In December 1999, it was recognized that a detailed plan needed to be developed and exercised for a controlled re-entry. Initial plans included an "Implementation Phase" for developing and testing ground procedures, using a preliminary mission design, before a critical failure occurred. These critical failures or "Trigger Points" would initiate an "Execution Phase" controlled re-entry process, including a final mission design. Before the detailed plan could be completed, the spacecraft lost the number 3 gyro. This accelerated the process. Procedures were developed and rehearsed using a preliminary mission design, as the final mission design was developed. Approximately one month before re-entry, all procedures were frozen and rehearsed with the final mission profile. The Flight Operations Team (FOT) and Applied Engineering and Technology Directorate (AETD) sub-system engineers repeatedly rehearsed various nominal and failure scenarios. Failure scenarios included thruster performance and failures, gyro and battery loss, through ground operations breakdowns.

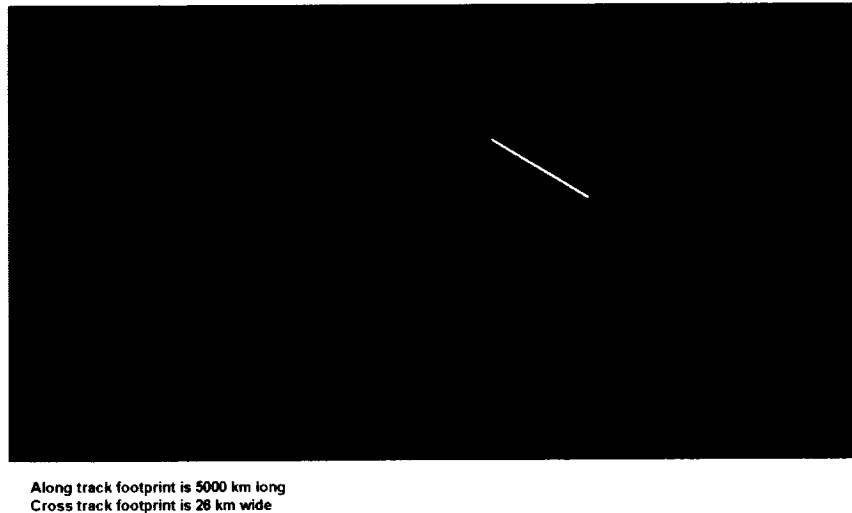
The re-entry maneuver scenario consisted of an engineering burn and four 26+ minute burns each centered at apogee that dropped the spacecraft from its 510 km circular orbit to a 510 x 50 km terminal orbit. On May 28<sup>th</sup> 2000, 19:44:00 GMT, the engineering burns were executed. These engineering burns consisted of short firings of the 5lb and 100lb thrusters to verify performance. Re-entry burn #1 was conducted on May 31<sup>st</sup> 01:51:05 GMT and put the spacecraft in a 510km X 350km orbit. Re-entry burn #2 was conducted on June 1<sup>st</sup> 02:36:52 GMT and placed the spacecraft in a 510km X 250km orbit. The final two re-entry burns were done on June 4 at 03:56:00 GMT and 05:22:21 GMT respectively. Re-entry burn 3 placed the spacecraft in a 510km X 150km orbit and re-entry burn 4 placed the spacecraft in its 510km X 50km terminal orbit. Within 30 minutes after the end of burn 4, the spacecraft had completed its re-entry into the Pacific. Confirmation of the re-entry from NORAD was received at approximately 10:00:00 GMT.

Between Burns 1, 2 and 3, the spacecraft remained in a power positive "Parking Attitude" under wheel control. Six minutes before the burn, the spacecraft entered Thruster Maneuver Mode (TMM) control and maneuvered to a "Burn minus 2 minute attitude" using the Attitude Control Thrusters (ACTs). At the burn minus 2 minute mark, the spacecraft pitched at 1 revolution per orbit to maintain the thrusters parallel to the velocity vector. A command from ground transitioned the controller to Velocity Control Mode (VCM) and fired the 100 lb Orbit Adjust Thrusters (OATs). During VCM, attitude control followed the velocity vector by on-modulating the ACTs for pitch and yaw and off-modulating the OATs for roll. An on-board timer automatically switched the controller back to TMM upon completing the burn. The spacecraft attitude continued to follow the velocity vector until a new parking attitude was loaded. After the slew to the

new parking attitude was complete, FOT commanded the spacecraft to a wheel based Normal Maneuver Mode (NMM). The attitude errors reduced to a level where an automatic switch to Normal Pointing Mode (NPM) occurred.

After Burn 3, the perigee altitude was reduced to approximately 150 km. At this altitude, aerodynamic torques would cause the controller to saturate the wheels. Therefore, the spacecraft remained under thruster control during a final perigee pass. On the next orbit, a 30 minute Burn 4 reduced the perigee to less than 50 km over the South Pacific Ocean. Figure 2-6 shows the predicted footprint, represented as the three stars connected by a line in the ocean. Since the burns were of nominal performance, the spacecraft objects fell around the green (center) star.

## June 4th Debris Footprint



**Figure 2-6. Predicted Debris Footprint**

The objects with a low mass to area ratio, i.e. the solar arrays, fell on the upper left side of the center star and the objects with a high mass to area ratio, i.e. the titanium bolts, fell down stream from the center star. All objects fell within the yellow (first) and white (third) stars. Visual contact from an U.S. Air Force plane, contracted by NASA to track re-entry, verified the proper time and location of impact. Further analyses are continuing to verify actual impact location of the debris.

[Technical contacts: [David Mangus](#), [Sue Hoge](#)]

### **2.2.4 TRMM Tropical Rainfall Measuring Mission Reentry Planning**

The TRMM scientists continue to be extremely pleased with the resolution of the science data provided by the tight pointing performance of the Attitude Control System (ACS). This data provides key information of the planet's energy balance by supplying previously unmeasurable total rainfall over the oceans as well as the continents. Periodic yaw and orbit raising maneuvers continue to hold TRMM at a constant 350 km orbit altitude and the Sun on the power positive side of the spacecraft.

The mission level and ACS design of the TRMM re-entry plan is being revisited due to the many lessons learned from the successful re-entry of the Compton Gamma Ray Observatory. Potential component failures and fuel levels are defined as "Trigger Points" and would begin the process of re-entry. Components that are not critical to re-entry or that have a work-around are also defined to extend mission life. New orbit maneuvers are being designed to incorporate the new requirements. Also, modifications to the ACS to maintain control at the lower altitudes are being investigated through simulation. A detailed debris analysis and impact foot print sizing is being coordinated with NASA/Johnson as well as the Aerospace Corporation.

[Technical contact: [David Mangus](#)]

### **2.2.5 General Space Operations Management Office (SOMO) Support**

The Space Operations Management Office (SOMO), located at Johnson Space Center, is an important sponsor and funding source for many of the FDAB activities. This includes much of the branch's technology work (covered in Section 4) as well as general mission design and concept development work for future missions (some of the work covered in Section 3 is sponsored by SOMO). The FDAB periodically assists SOMO in its management of mission services and operations activities, including its management of the Consolidated Space Operations Contract (CSOC). This may be assistance to CSOC in spacecraft anomaly resolution or identification of future mission services. During FY00, the FDAB supported the following SOMO activities:

- Technical review of progress by the Flight Dynamics Facility (FDF) to implement the real-time orbit determination (RTOD) system
- Formal monthly status reviews to the Goddard Network and Mission Services Project by the FDF
- Preparation of material to be included as part of the "SOMO Architectural Evolution Plan" which identifies roadmaps for future mission service upgrades and technologies
- Preparation and review of updates to the SOMO Mission Services Catalog

FDAB management meet regularly with CSOC management responsible for the operation of the Flight Dynamics Facility. The purpose of these meetings is not to give direction to routine operations, but to continue to maintain awareness of facility upgrade plans and share knowledge of future mission plans, technology development activities relevant to the facility, and software system upgrades.

[Technical Contact: Tom Stengle]

## **3.0 Study Mission Support**

One of the primary roles of the Flight Dynamics Analysis Branch (FDAB) within the Guidance, Navigation and Control Center (GNCC) is to serve the science community by providing analysis of advanced mission concepts. This includes development of orbit/attitude designs based on science constraints, evaluation of orbit/attitude errors and attitude dynamics analysis. Members of the branch often represent "first access" by Earth Science and Space Science customers to the services offered by the GNCC and the Space Operations Management Office (SOMO).

In FY2000, the GNC continued its participation in supporting a wide variety of future mission concepts. This section describes some of the analyses performed.

### **3.1 IMDC Integrated Mission Design Center**

The Integrated Mission Design Center (IMDC) is a human and technology resource dedicated to innovation in the development of advanced space mission design concepts to increase scientific value for NASA and its customers. The IMDC provides specific engineering analysis and services for mission design, and provides end-to-end mission design products. For information about the IMDC, please refer to URL <http://imdc.nasa.gov/default.htm>

Flight dynamics analysis support, in the areas of trajectory design, orbit analysis, mission planning; and ACS design, hardware selection and performance evaluation, was provided in the IMDC for a variety of future mission studies. Collaboration studies with the Jet Propulsion Laboratory (JPL)'s Team X were performed for the Ocean Surface Salinity Mission (OSSM) and Nanosat Technologies. Some of the Earth Science Missions supported were Radiation Belt Mapper (RBM), Ionospheric Mapper (IM), Global Precipitation Mission (GPM), Ocean Observing Study (OOS), and Ocean Salinity Mission. The Interplanetary and Space Science Missions supported included Marsat, DS-5, Solar Sail, DS-5 Constellation, and Solar Dynamics Observatory. A total of 8 flight dynamics analysts supported various IMDC sessions this year: Marco Concha, Steven Cooley, David Folta, Lauri Newman, Gregory Marr, Michael Mesarch, Josephine San, and Frank Vaughn.

[Technical contacts: Marco Concha, Josephine San]

### **3.2 Ana Lani**

The Ana Lani mission concept is from a joint team of scientists from Goddard, University of Washington, University of Michigan and University of Hawaii. The science objective is to generate a map of the mass distribution in the universe to find cosmological constants. The instrument consists of 12 modular foil mirrors, each with a 24-cm diameter and 1.7 m focal length. Although the pointing requirement is in arc minutes, the jitter requirement is 2 arc seconds over 20 second.

In addition to the general support provided while the mission was studied in the IMDC, ACS personnel performed analysis to show the feasibility of inertial pointing with a 5 degree Sun pointing constraint, and defined the star tracker optimal location.

[Technical contact: Josephine San]

### **3.3 Fluorescence Experiment (FLEX)**

Flex is an earth observing mission proposed by the University of New Hampshire in response to an Announcement of Opportunity (AO). This mission will use the existing Fabry-Perot spectrophotometer to measure chlorophyll fluorescence and to monitor globally the stress in vegetation. In support of this low cost mission, FDAB personnel performed a feasibility study of the minimum wheel configuration to perform 180 degree slews; investigated control laws for initial Sun acquisition and safe mode; and carried out attitude sensor trades to develop a minimum hardware ACS design.

[Technical contact: Josephine San]

### **3.4 Global Precipitation Mission (GPM)**

The Global Precipitation Mission (GPM) concept study was supported by the FDAB. GPM seeks to deploy a constellation of spacecraft that will provide global rainfall measurement coverage with a 3 hour latency. FDAB involvement this year has been to provide feasibility analysis for the design, deployment and maintenance of the constellation. GPM is a TRMM follow on mission. It consists of a core spacecraft similar to TRMM and a constellation with 6 small spacecraft in a 6-pedal orbit configuration. It is a joint venture of Goddard and Japanese scientists. The mission concept was brought to the IMDC three times for different levels of study.

In addition to the routine ACS analysis and design, FDAB personnel provided special analysis in the following two critical system level design issues. First, the constellation satellite instrument Lightweight Rainfall Radiometer (LRR) spinning at 8 rpm is located over a meter from the spacecraft center of gravity. This imposes a critical issue on the spacecraft jitter performance. FDAB personnel performed a detailed analysis on the effect of the LRR imbalance on jitter and defined the LRR offset limit based on a two-body model. Secondly, the core spacecraft in a 70 degree inclination orbit requires large solar arrays, which induce disturbance torque due to plume impingement, as well as other flexibility issues and thermal snapping. FDAB personnel supported the solar array design trade from the ACS perspective.

A next generation GPM (GPM Next) study was carried out together with JPL. FDAB personnel worked with scientists to derived ACS pointing and jitter requirement due to a finer resolution instrument. The IMDC and JPL investigated the newest sensor and actuator technologies to put together a lightweight, low power, and low cost ACS system.

[Technical contact: Marco Concha, Josephine San]

### **3.5 Joule**

Joule is an X-ray astronomy mission concept in response to NASA's Small Explorer (SMEX) Program. FDAB engineers worked in the IMDC to provide analysis and design support to complete a mission proposal. Special ACS trades on the maximum slew angle vs. wheel momentum and torque capabilities were performed to reach an optimal design in mass, power, and cost. The proposal was selected as a first round candidate for the SMEX program.

[Technical contact: Josephine San]

### 3.6 Mars Areo-stationary Relay Satellite (MARSAT)

MARSAT is a proposed Mars orbiting communication satellite for the Mars Communication and Navigation Infrastructure to be led by JPL. This satellite will use a 2.5-m Ka-band High Gain Antenna (HGA) to communicate with the earth and a 1-m x-band HGA to relay other Mars orbiting satellites and Mars's landers to MARSAT. Jitter requirements and recovery from anomalies are major concerns.

FDAB personnel performed rigid body jitter analysis to show the feasibility of 1 dB beam width for the earth link, performed flexible mode analysis, defined transfer orbit scenarios, evaluated control mode design approaches, and investigated hardware lifetime to ensure a 9 year mission life. Most importantly, FDAB personnel investigated and defined two levels of safe mode, and derived control schemes and operational scenarios to search for the earth.

[Technical contact: [Josephine San](#)]

### 3.7 Living With a Star (LWS)

The Flight Dynamics Analysis Branch has been involved in the formulation of missions for the Living with a Star Program. The FDAB was involved with the generation of orbits and products related to a distributed system of spacecraft used to understand the Earth's environment and the interaction with the Sun. Several missions are supported in this area including Inner Heliospheric missions that use a Venusian gravity assist to align the spacecraft into their respective positions. A sample of these missions is highlighted below. Each orbit represents a single spacecraft after a Venus encounter. A second concept dealt with the attainment of a Sun Earth L3 orbit. A figure describing this orbit is also provided (Figure 3-1). The travel time to the L3 location was of concern and resulted in several options for drift away style trajectories. Figures 3-2 and 3-3 show the transfer trajectories and the final L3 orbit.

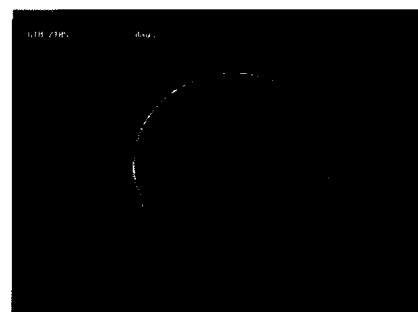


Figure 3-1.

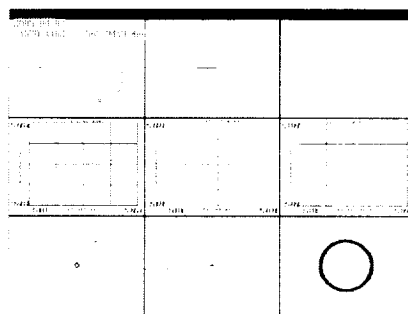


Figure 3-2.

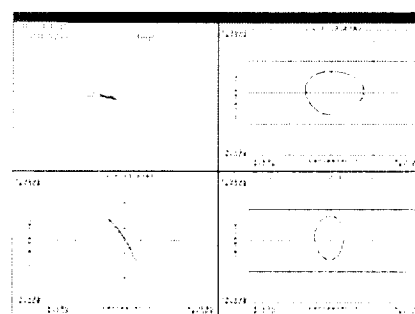


Figure 3-3.

This mission concept consists of four individual missions: Solar Dynamics, Radiation Belt Mapper (RBM), Ionosphere Mapper (IM), and Inner Heliospheric Sentinels (IHS). Each mission has its unique objectives and design challenges.

Solar Dynamic is a solar observer performing continuous and high cadence observations of the full solar disk and coronal imaging in multiple wavelengths to improve understanding and forecasting of the Sun's impact. The pointing requirement is tight, especially the jitter requirement (0.25 arc second /45 second). FDAB personnel investigated jitter performance using the output from the guide telescope to close the control loop.

RBM is a mission to establish magnetic field properties of the radiation belt. 6 spacecraft will be stacked in one launch vehicle and placed in 6 highly elliptical orbits, 4 in 500 km x 6.5 Re and 2 in 500 km x 2.5 Re. RBM is a spinner with spin axis 15 degrees from the Sun line.

The IM mission objective is to monitor the global plasma environment using tomography and to study Ionosphere density, gas properties, and magnetic and electrical fields. Eight spacecraft with 6 on one launch vehicle and 2 on another, will be placed in low earth orbit in 3 different inclinations.

IHS is a solar orbiting mission measuring the electric and magnetic field of the Sun. Four spacecraft will be stacked on one launch vehicle. The spacecraft is a spinner with spin axis pointing at the Sun.

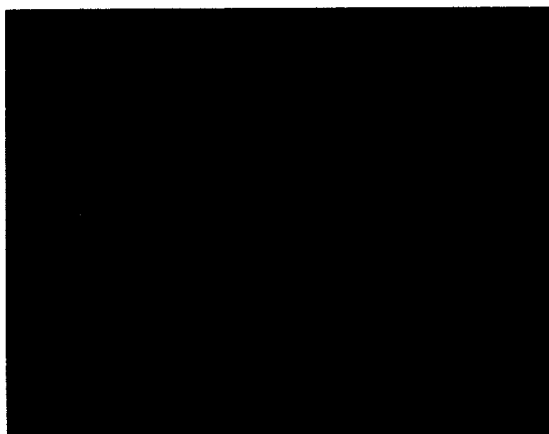
The challenging problem for RBM, IM and IHS is the separation and deployment due to the stacking of multiple spacecraft on one launch vehicle and placement in different orbit configurations. FDAB personnel worked along with system, mechanical and power engineers to define feasible operations scenarios, and sub-optimal control design approaches.

For RBM and HIS, having the spin axis not normal to the orbit plane but toward the Sun raises issues of appropriate attitude sensors. FDAB personnel worked with the project scientist to refine the requirements, trading science objective, sensor cost and control complexity.

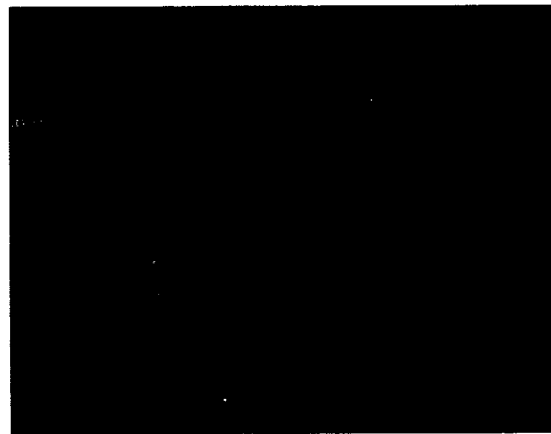
[Technical contact: David Folta, Josephine San]

### **3.8 NGST/Nexus**

The Next Generation Space Telescope (NGST) and its technology demonstration support mission called NEXUS were studied as part of the formulation phase. Several trajectory designs were investigated for possible use. The support provided by the FDAB allowed the NEXUS project to understand fuel, DV, and launch vehicle impacts due to trajectory design. Work performed both at the IMDC and afterward resulted in a clear understanding of the orbit constraints and requirements. A sample trajectory design is shown below for this L2 co-linear Sun-Earth/Moon mission orbit (figures 3-4 and 3-5).



**Figure 3-4.**



**Figure 3-5.**

The objective of NEXUS is to provide a pathfinder to demonstrate technology required for the Next Generation Space Telescope (NGST). This includes a demonstration of lightweight, actively controlled, cryogenic optics for astronomical observations in the infra red region and a demonstration of disturbance torque isolation and ACS control with a large solar mask. Since this an L2 mission, the momentum unloading will be achieved with thrusters and is required to execute as infrequently as possible due to tight jitter requirements (1 arc second over 1000 second). The pitch axis tilt angle requirement, from 85 to 135 degrees from the Sun line, also imposes a challenge in the ACS design.

FDAB personnel performed detailed solar torque analysis to bound the pitch tilt angle and offset between center of pressure and center of mass. They also developed a relationship between solar torque and the momentum unloading frequency and wheel momentum and torque capability requirements. Detailed rigid body jitter analysis was performed to demonstrate the importance of flexible mode analysis and the necessity of disturbance torque isolation.

[Technical contacts: David Folta, Josephine San]



### **3.9 NPP**

The National Polar-orbiting Operational Environmental Satellite System (NPOESS) Preparatory Project (NPP) is a risk-reduction demonstration mission. Another objective of NPP is to provide a continuation of measurements of global change parameters after EOS Terra and Aqua. FDAB personnel evaluated several Rapid Spacecraft Development Office (RSDO) buses to converge on a suitable selection based on quick and simple analysis on the sensor performance, actuator capability for all modes and detailed rigid body jitter analysis. Per the science requirement, two levels of safe mode control were designed and an operational scenario for each level was defined.

[Technical contact: [Josephine San](#)]

### **3.10 Ocean Surface Salinity Mission (OSSM)**

FDAB personnel provided analysis support for the Ocean Surface Salinity Mission (OSSM) concept which is planned to be submitted in response to the next ESSP AO. The purpose of the proposed mission is to understand processes that control the transport, storage and exchange of fresh water between Earth's atmosphere, land, oceans, and polar regions.

FDAB personnel supported the development of the mission concept by performing analysis for several instrument design concepts to identify suitable candidate orbits that will meet the mission's data collection requirements. The mission concept was studied in the Integrated Mission Design Center (IMDC) to identify the impact of the candidate instrument designs on the spacecraft design. The IMDC study resulted in narrowing the field of practical candidate instrument designs, and identified key cost and complexity trade issues for the spacecraft design that result from both fixed and rotating instrument designs. The science team is now in the process of evaluating these issues to select the instrument design that provides the best performance without exceeding the cost and schedule constraints for the mission. FDAB personnel will continue to provide analysis support as the proposal moves toward submittal.

Attitude determination and control design and analysis support for the Ocean Surface Salinity Mission concept was also provided. For each instrument design, trades were performed to identify the impact on ACS hardware mass, power and cost. Low-fidelity simulations were performed to prove the control concepts and control mode design options were investigated.

[Technical contacts: [Frank Vaughn](#), [Josephine San](#)]

### **3.11 Solar Sail**

The Solar Sail mission is a solar sail technology flight demonstration. Its objectives are to validate an integrated solar sail flight system with low volume packages, and to characterize the use of large solar sails for future science observations.

FDAB personnel investigated the pros and cons of gaining 3-axis control by using a sliding mass to offset the center of gravity or by manipulating trim tabs to offset the center of pressure from the center of mass. The trim tab approach is superior from an ACS perspective, but increases integration complexity. FDAB personnel identified limitations and concerns using solar sails as control actuators.

[Technical contact: [Josephine San](#)]

### **3.12 Constellation X**

Constellation X is a study mission that uses 4 x-ray telescopes in constellation at the Earth's L2 libration point to study black holes and galaxy formation. The instrument consists of a large area X-ray mirror with 100-meter focal length. Therefore, the detector will be on a 100-meter long boom with 50-kg mass and 1 square meter of Sun shield area, which induces large disturbance torque on the spacecraft. This year the FDAB has provided support to the Constellation X study team in the areas of orbit determination accuracy and trajectory design. The baseline plan is to launch the spacecraft in pairs aboard 2 Delta IV or Atlas V launch vehicles. The FDAB is designing the baseline trajectory to accomplish

this scenario. Also, in the event that the larger launch vehicles are not available in the 2008 mission timeframe, there is a study underway to determine the feasibility of launching the 4 spacecraft on 4 Delta II vehicles, then using a combination of hydrazine and low-thrust propulsion to achieve the desired mission orbit. Various low-thrust options are being considered, and the FDAB is studying the available constant thrust trajectory options.

FDAB personnel also assessed possible spin rates and slew constraints, studied the feasibility of spinning optics for thermal control, pinpointed momentum unloading concerns due to significant disturbance torque and momentum build up, and investigated dual spin spacecraft stability criteria and performance capability.

[Technical contact: Lauri Newman]

### **3.13 Magnetospheric Multiscale Mission (MMS)**

The MMS mission is a four-spacecraft Solar-terrestrial Probe designed to study magnetic reconnection, charged particle acceleration, and turbulence in key boundary regions of the Earth's magnetosphere. The mission is in its study phase. The Announcement of Opportunity (AO) for the instrument complement and Principle Investigator teams is expected to be released in the summer of 2001.

The analysis tasks are directed toward characterizing the orbit dynamics of the mission, in part because they are needed for the AO, but also because spacecraft design is underway and subsystem engineers need to know them. The orbits are highly elliptical. Near apogee, the size of the tetrahedron formed by the four spacecraft varies over the life of the mission, hence the term 'multiscale' in the mission name. The analysis tasks include demonstrating that trajectories can be designed to meet the science and engineering requirements, determining how to control the trajectories and the amount of propellant required to do so. In parallel, a statement of requirements is being developed by the orbit analyst in consultation with the MMS study management and science team. The requirements are evolving as the analysis proceeds and characteristics become known.

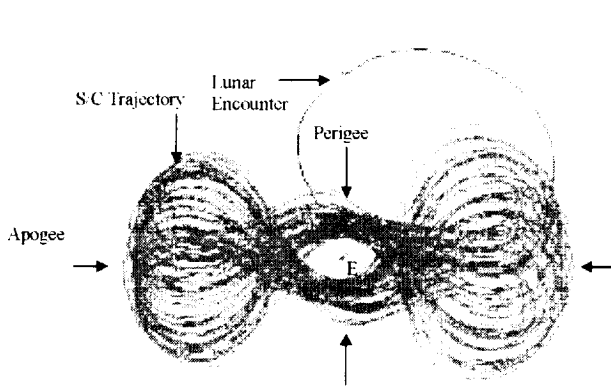
Little of the software needed to execute the studies is in the "off the shelf" category because this is not a routine mission for which analysis techniques are readily available. Software has been developed to the prototype level that finds and analyzes suitable trajectories. A graphics program was written to illustrate the behavior of the tetrahedron as it changes size and shape throughout each orbit.

For more detailed information about the mission, visit <http://mms.gsfc.nasa.gov>.

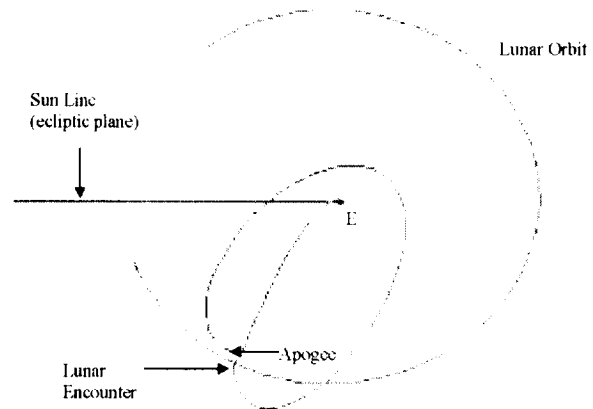
[Technical contact: Charles Petruzzo]

### **3.14 KRONOS**

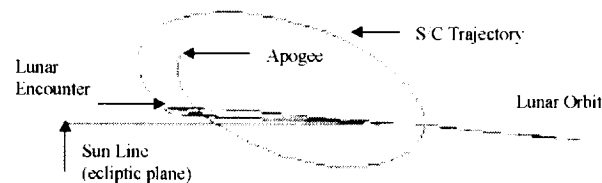
The FDAB completed an extensive mission feasibility study for the KRONOS Mission High Earth Orbit (HEO). This unique orbit requires a lunar swingby to increase the orbit perigee radius, lift the orbit out of the ecliptic plane, and rotate the line of apsides such that apogee is in the northern hemisphere. The final HEO orbit obtained via this lunar swingby has perigee near 10 Earth Radii ( $R_E$ ) and apogee near lunar distance ( $\approx 60 R_E$ ). A final study report contained a detailed analysis of the HEO orbit characteristics, launch window opportunities, and fuel budget estimates. The results, presented to the KRONOS Project. Deputy PI, were well received and will be used as part of future mission proposals for KRONOS and other missions. The KRONOS trajectory is shown in figures 3-6, 3-7, and 3-8.



**Figure 3-6 KRONOS Direct Transfer HEO (5 year Mission), View in Earth – Moon Rotating Coordinates (June 1)**



**Figure 3-7 KRONOS Direct Transfer HEO (Post Lunar Encounter Apogee), View from North Ecliptic Pole in Solar Rotating Coordinates (June 1)**



**Figure 3-8 KRONOS Direct Transfer HEO (Post Lunar Encounter Apogee), View in ecliptic Plane in Solar Rotating Coordinates (June 1)**

[Technical contact: [Steven Cooley](#)]

### **3.15 Leonardo**

Leonardo-BRDF is a new NASA mission concept proposed to allow the investigation of radiative transfer and its effect on the Earth's climate and atmospheric phenomenon. Enabled by the recent developments in small-satellite and formation flying technology, the mission is envisioned to be composed of an array of spacecraft in carefully designed orbits. The different perspectives provided by a distributed array of spacecraft offer a unique advantage to study the Earth's albedo. Over the past year the Flight Dynamics Analysis Branch has been investigating formation flying dynamics concerns in the context of the Leonardo-BRDF science requirements. Together with scientists we have investigated the albedo integral and the effect of viewing geometry on science return. An approach based on Gauss quadrature has been investigated to provide the optimal formation geometry to ensure that the value of the integral is accurately approximated. Secondly, strategies have been developed to achieve the desired orbit geometries within the constraints of orbit dynamics. Both linear and non-linear techniques have been developed for two types of formations such that all orbits composing the formation have the same node rate and mean anomaly rate respectively, in the presence of  $J_2$ . The relative geometry afforded by each design has been investigated in terms of mission requirements. An optimal Lambert initialization scheme has been implemented to obtain preliminary estimates of the required Delta-V to distribute all spacecraft from a common parking orbit into their appropriate orbits in the formation. Finally, formationkeeping strategies have been developed and the associated DV's are calculated to maintain the formation in the presence of perturbations.

[Technical contact: [Steven Hughes](#)]

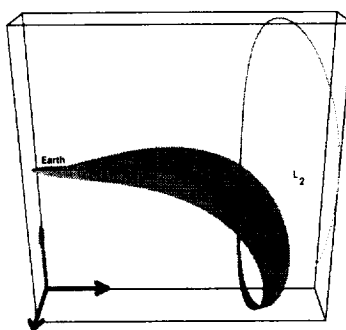
## **4.0 Technology Development Activities**

### **4.1 Advanced Mission Design**

The Goddard Space Flight Center's (GSFC) Guidance Navigation and Control Center (GNCC) is at the forefront of libration orbit mission design, algorithm and software development, and their application to libration point missions. This mission design encompasses the detailed analysis of attaining and maintaining Sun-Earth/Moon libration orbits via direct and lunar gravity assist transfers. Upcoming missions such as the Microwave Anisotropy Probe (MAP), Triana, and the Next Generation Space Telescope (NGST) are addressed in light of improved methods for attaining constrained orbits parameters and their control at the collinear libration points. New developments such as invariant manifold theory and optimization based on eigenvector formulation to achieve constrained orbit parameters is currently under investigation.

Sun-Earth libration point orbits serve as excellent locations for scientific investigations. These orbits are often selected to minimize environmental disturbances and maximize observing efficiency. Trajectory design in support of such missions is increasingly challenging as more complex missions are envisioned in the next few decades. Trajectory design software must be further developed to incorporate better understanding of the libration orbit solution space and thus improve the efficiency and expand the capabilities of current approaches. Only recently applied to trajectory design, dynamical systems theory now offers new insights into the natural dynamics associated with the multi-body problem. In a cooperative effort, the Goddard Space Flight Center's (GSFC) Guidance Navigation and Control Center (GNCC) and Purdue University are working together to develop this expertise.

Nonlinear dynamical systems theory (DST) offers new insights in multi-body regimes, where qualitative information is necessary concerning sets of solutions and their evolution. DST is, of course, a broad subject area. The DST work has been performed in partnership with Purdue University. At Purdue University, various dynamical systems methodologies are included in a software package called Generator. In Generator, different types of solution arcs, some based on dynamical systems theory, are input to a process that differentially corrects the trajectory segments to produce a complete path in a complex dynamical model. A two level iteration scheme is utilized whenever differential corrections are required; this approach produces position continuity (first level), then a velocity continuity. An understanding of the solution space then forms a basis for computation of a preliminary solution and the end-to-end approximation can then be transferred to GSFC operational software for final adjustments for launch window, launch vehicle error analysis, and maneuver planning. The current goal is to blend dynamical systems theory, which employs the dynamical relationships to construct the solution arcs, and the mission design tool Swingby, with its strength in numerical analysis. A sample of the trajectories calculated using Generator is shown in figure 4-1.



**Figure 4-1. Sample of Trajectories Using Generator**

[Technical Contact: [David Folta/572](#)]

### **4.2 Autonomous Onboard Navigation Systems**

Increasing interest in maximizing autonomy, operations "beyond LEO," and distributed spacecraft has brought new challenges for navigation systems. Addressing and anticipating new requirements has led to technology initiatives in

onboard navigation systems (ONS) using communications links, Global Positioning System (GPS) orbit determination, and autonomous navigation for high-Earth, libration, gravity-assist, and deep-space orbits.

FDAB work develops and infuses autonomous navigation technologies for Earth orbiting, libration point, and deep space missions. In so doing, it enables highly accurate autonomous onboard inertial and relative navigation for multiple satellites, which reduce the cost of autonomous navigation implementation and testing while increasing the efficiency of the navigation process. The work is divided into four areas:

- GPS Navigation: Enhances the GPS Enhanced Orbit Determination (GEODE) flight software to support all near-Earth absolute and relative navigation requirements and support its integration with one or more prototype GPS space receivers
- Onboard Navigation Systems (ONS) using Communications Systems: Provides onboard navigation system for non-GPS missions by integrating ONS flight software used on the EUVE & Terra spacecraft with a Navigation Processor Board (NPB) within the communications system
- Relative Navigation: Determines the performance of relative navigation for various mission concepts via crosslinks and/or GPS, and develops a crosslink receiver
- Celestial Navigation: Develops an autonomous onboard system that infuses new ground-based navigation filter processes with onboard attitude and/or Doppler measurements

During the past year, several of these tasks have experimented with an increasingly convergent software development process. These two subtasks have been able to leverage common elements in navigation filter design and software architecture to accomplish substantially more development and analysis combined than either could alone. In most upcoming work, it is planned to fold all the tasks into this software process, thereby allowing all to share the overhead of software development and maintenance, where possible. The unified software package, GPS-Enhanced Orbit Navigation System (GEONS), is designed so that although all subtasks' capabilities are resident in the source code, only those elements that are necessary for each specific application are switched on when the package is compiled. This design allows the package to remain lean and fast enough to be considered for onboard flight software applications, as well as ground support and analysis functions. The result is a multi-purpose navigation software package that maximizes software reusability and maintainability, and can be easily reconfigured to a user's needs.

The GEONS software uses heritage code to reduce errors and assure reliability and compatibility, which is based on flight-proven ground-based (GTDS) and onboard (TONS) navigation systems. The software has been and will be verified using realistic simulation data and actual satellite data for analysis & testing, including actual satellite data from EUVE, Terra, Polar & the Solar and Heliospheric Observatory (SOHO), and hardware-in-the-loop testbeds consisting of GPS signal simulators and closed-loop orbit control capabilities. Measurements will currently include GPS, Federal Aviation Administration (FAA) Wide Area Augmentation System (WAAS), and intersatellite crosslinks, and are planned to include ground station measurements, TDRSS, star, Sun, lunar, and Earth sensor measurements, and forward-link Doppler measurements from command link carrier. During the past year, integrated testing between hardware and software has been initiated for GPS and EONS target platforms. These have included an in-house open-architecture GPS receiver (PiVoT), ITT's low power transceiver (LPT), and, the Motorola Navigation Processor Board for their 4th Generation Transponder (the latter, due to heritage interface structures, does not use GEONS). In its GPS-only incarnation, GEODE, the GEONS software was GSFC Software of Year, and was NASA's Software of Year Runner-Up.

Web-based team collaboration, using concurrent version system (CVS) code management, has allowed a diversity of teaming arrangements, involving government, support contractors, universities, and licensees. These have included GSFC, LaRC, Computer Sciences Corporation, the University of Colorado at Boulder, Orbital Science Corporation, Ball Aerospace, ITT, Motorola, and the Johns Hopkins Applied Physics Lab. These collaborations and technology transfers have lead to numerous current and planned infusion of our autonomous navigation systems, as listed below:

- GEODE flight qualified for Lewis mission
- GEODE Lite to fly on EO-1
- GEODE is being transferred to LaRC for evaluation of use by Pathfinder Instruments for Cloud and Aerosol Spaceborne Observations - Climatologie Etendue des Nuages et des Aerosols (Picasso-CENA) (Earth System Science Pathfinder /ESSP)

- Potential use of GEODE on proposed Earth Science missions (Magnetic Multi-scale Mission (MMS), Auroral Lights) under discussion with scientists and project engineers
- Plan to solicit missions based on Terra success for EONS
- Current analyses using Aurora Lites, MMS for Relative Navigation mission studies
- CelNav system can be used for ground based navigation
- CelNav "Flight Code" may be included in Discovery mission
- GEODE licensed to Orbital Sciences Corporation for use on OrbComm
- OSC expressed interest in embedding GEODE filter into a space-qualified version of their Ashtech G12 GPS receiver
- License agreement in place with MIT/Lincoln Labs via DoD, and with Ball
- License agreements are in negotiation with UCLA & CU/Boulder
- Agreement with ITT for infusion into Low Power Transceiver for Shuttle demo
- EONS/GEODE potential for commercialization by Motorola in their receiver units
- Relative Navigation potential for commercialization when integrated with crosslink receiver (APL, Motorola, ITT)
- CelNav potential for commercialization when integrated with GEODE, RelNav or EONS

Below, more detailed descriptions of the past year's accomplishments are given for FDAB autonomous onboard navigation system technology.

#### **4.2.1 Terra Onboard Navigation - The TDRSS Onboard Navigation System (TONS)**

Terra is flying an autonomous onboard navigation system to provide accurate orbital parameters to the spacecraft in real time. The system, known as the TDRSS Onboard Navigation System or TONS, is another first for NASA by flying onboard navigation as the operational system for orbit solutions.

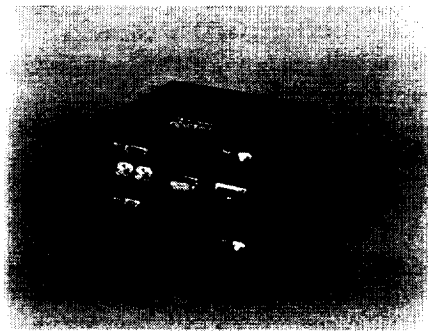
TONS measures the Doppler data off the forward communications signal from Tracking Data Relay Satellite System (TDRSS) and processes it in onboard software with a sequential estimation algorithm to produce the real time outputs. The accuracy requirement for TONS is 150 meters in position and 0.16 meters per second in crosstrack velocity, 3 sigma. TONS performance has far exceeded the requirement. TONS compares to traditional orbit determination methods to 7 meters, one sigma in position and better than 0.015 meters per second in crosstrack velocity. After on-orbit tuning, TONS is expected to provide Terra with onboard position knowledge to better than 5 meters, one sigma and 20 meters, 3 sigma. TONS performance was monitored during the Terra ascent maneuvers and indicated excellent recovery within the first few measurement updates after the maneuver. TONS filter reconvergence occurs at the beginning of the second post-maneuver contact. TONS has since been used as the operational solution during the station-keeping maneuvers, staying within the 150 meter position requirement. TONS also estimates the local oscillator frequency, a drag correction factor, and a TDRS measurement bias for Terra. All on-orbit requirements have been exceeded and navigation operations have been performed nominally. TONS data was also used to calibrate the spacecraft clock to aid the operational clock correlation system. Terra scientists obtain the real-time TONS navigation solution in their ancillary data.

[Technical contact: [Cheryl Gramling](#)]

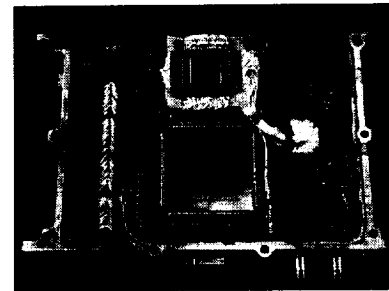
#### **4.2.2 Onboard Navigation Systems Using Communication Links**

The Enhanced ONS (EONS) flight software package is an integrated navigation system, which can be procured as an option to the existing spacecraft communications equipment. For those requiring autonomous navigation, EONS will be significantly cheaper and more reliable than independent software development and system integration efforts. EONS is derived from TONS, which flew on EUVE and Terra. It is being integrated into a Nav Processor Board (NPB) that will be part of Motorola's 4th Generation Transponder (figure 4-2).

## Fourth Generation Transponder



NPB, Top



NPB, bottom

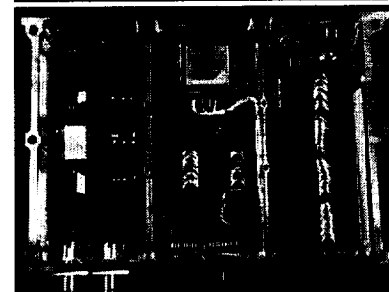


Figure 4-2. Navigation Processor Board

Highlights of the past year's accomplishments are

- TONS software successfully used to support Terra operations
- Developed 1553 Interface Software for executive/driver, embedded processor, and Special Test Equipment
- Developed Improved Method for Doppler Extraction (by Motorola & Government)
- Generated simulated truth data by modifying existing program to increase validity and realistic qualities of the data
- Hosted EONS code on Navigation Processor Board and performed initial testing

[Technical contact: [Cheryl Gramling](#)]

### 4.2.3 Global Positioning System Advanced Concepts

Global Positioning System (GPS) satellite navigation is a proven technology that provides potential for low-cost autonomous satellite navigation systems. The current GPS algorithms, software, receiver hardware, and simulators, however, need to be enhanced to broaden the mission scope to include all near-Earth missions, such as highly elliptical orbits (HEO) and geosynchronous Earth orbits (GEO), as well as to support relative navigation for formation flying applications. This project is enhancing the GPS Enhanced Orbit Determination Experiment (GEODE) flight software to support such missions, and support its integration with one or more prototype GPS space receivers. Figure 4-3 shows the GPS signal.

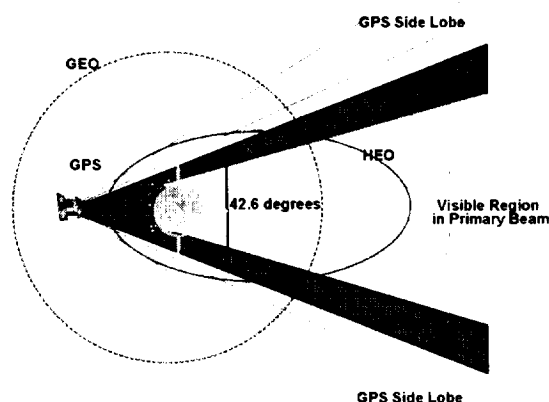


Figure 4-3. Satellite Orbital Geometry With Respect to GPS Broadcast Signal

Highlights of the past year's accomplishments are:

- Won GSFC Software of the Year, and Runner-up for NASA Software of the Year
- Major new GEODE release (V5) supporting relative navigation in HEO and GEO missions, and relative navigation
- Enhanced data simulation capabilities to support weak signal tracking analysis for HEO and GEO missions
- Initial integration with PiVoT GPS Receiver & ITT Low Power Transceiver
- Papers presented to International GPS Workshop & International Flight Dynamics Conference concerning HEO and GEO capabilities and projected performance
- Supported formal Peer Review for Explorers Technology Development Program

A paper was presented at the International Symposium on Space Flight Dynamics in Biarritz, France. This paper discusses autonomous navigation improvements for high-Earth orbiters and assesses projected navigation performance for these satellites using Global Positioning System (GPS) Standard Positioning Service (SPS) measurements. Navigation performance is evaluated as a function of signal acquisition threshold, measurement errors, and dynamic modeling errors using realistic GPS signal strength and user antenna models. These analyses indicate that an autonomous navigation position accuracy of better than 30 meters root-mean-square (RMS) with selective availability (SA) enabled and 10 meters RMS with SA disabled can be achieved for high-Earth orbiting satellites using a GPS receiver with a very stable oscillator. If the GPS receiver's signal acquisition threshold can be reduced by 5 dB-Hertz to track weaker signals, this accuracy improves to better than 20 meters RMS with SA enabled and 8 meters RMS with SA disabled. Figures 4-4 and 4-5 show the RMS error margins.

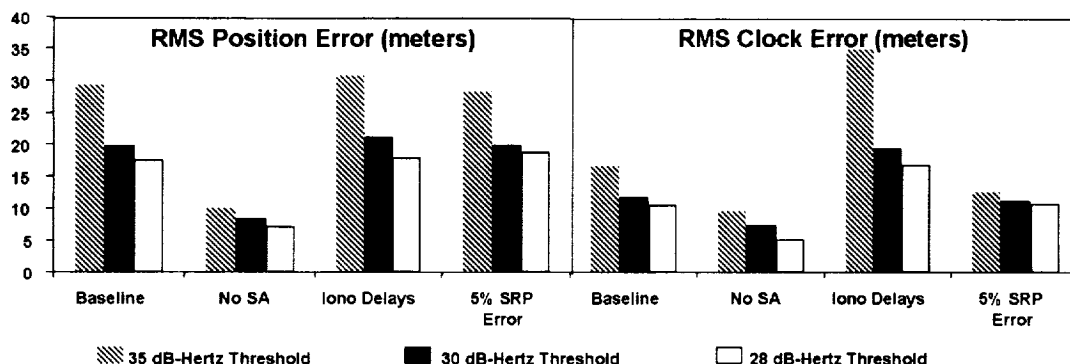


Figure 4-4. Comparison of Steady-State Time-Wise Ensemble RMS True Errors for HEO

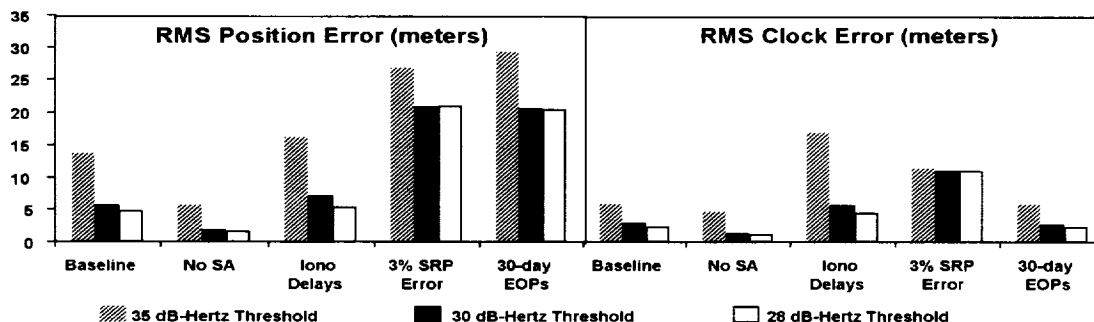


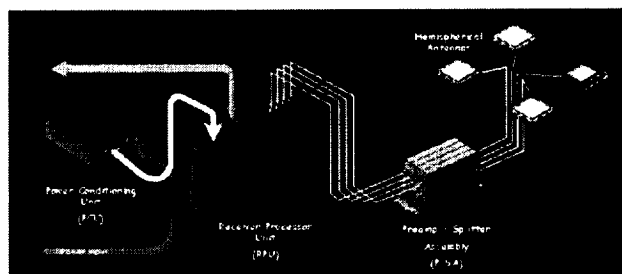
Figure 4-5. Comparison of Steady-State Time-Wise Ensemble RMS True Errors for GEO

[Technical contact: [Russell Carpenter](#)]



#### **4.2.4 EO-1 Global Positioning System (GPS)**

The Earth Observing-1 (EO-1) spacecraft launch is currently planned for November 16, 2000, from Vandenberg Air Force base. Since the integration of the Tensor GPS receiver to the EO-1 spacecraft in March of 1999, subsequent tests demonstrated that the integration was successful and that the spacecraft was ready for thermal vacuum testing. The spacecraft was then moved from the construction site at SWALES into the Goddard's building 7 test facility. The first series of thermal vacuum tests were run in November of 1999. During these tests, the GPS receiver was exposed to and operated in no less than two cold soak plateaus each lasting a minimum of 24 hours and two at hot soak plateaus of similar duration. During these tests, the GPS flight system performed flawlessly. However, the same could not be said of the ground support equipment (GSE). Intermittent data dropouts experienced during testing were later found to be a direct result of the poor RF characteristics of the GSE cables used to bring GPS signals from the rooftop antenna to the test chamber. The flight system was deemed ready to fly and the GSE would be upgraded for any subsequent tests. Figure 4-6 depicts the GPS receiver.



**Figure 4-6. EO-1 GPS Receiver**

By April 2000, the EO-1 ground system was upgraded to allow the GPS flight receiver to be warm started from the MOCC. In a cold start, the receiver is powered on, configured for orbital operations and allowed to acquire a navigation fix with no further interaction required. This type of self acquisition can be very time consuming (on the order of hours) and may not always be practical in an operational environment. For this reason, it was deemed necessary for the ground system to be capable of executing a warm start of the GPS receiver. In a warm start, the receiver is powered on, configured for orbital operations and provided a GPS almanac file (position data of the 32 GPS satellites) and an ephemeris file (position data of the EO-1 spacecraft). Given this information, the GPS receiver can begin acquiring GPS satellites and generating navigation solutions in only a few minutes. Warm starting the receiver from the MOCC would require software to allow generation and uplink of almanac and ephemeris data. This is a capability even the manufacturer of the GPS hardware does not possess. Since thermal vacuum testing would be employing the MOCC software to communicate with the EO-1 spacecraft, this newly developed capability would also be tested during the second set of thermal vacuum tests.

From a thermal vacuum testing standpoint, the GPS tests were an unqualified success. Not only did the receiver perform as expected (just as it did during the first set of TV tests), but the new and improved GSE proved reliable as well. This new and improved GSE could now be used at the launch pad for any testing requiring real time GPS data. After a few minor bugs were corrected, the MOCC software was proven to enable a flight operator to download a GPS YUMA almanac file from the Coast Guard navigation web site (where all GPS almanacs are archived) and construct a flight load from the data. In a similar manner, the MOCC was enabled to employ ground orbit data to generate an ephemeris load to the GPS receiver. Given these data, the receiver was able to acquire GPS satellites and begin producing navigation fixes in a relatively short time (several minutes). This capability was tested against the flight GPS using many different YUMA files while receiving GPS inputs from first the actual constellation then from the GPS constellation simulator.

Finally only one difficulty remained. The MOCC ground system was unable to translate atypical (Bus-B) housekeeping telemetry downloads. Routine GPS navigation solutions are fed to the EO-1 ACS via the main telemetry bus (Bus-A). This includes position, velocity and time data. From these data, the EO-1 ACS is able to create the reference frame against which attitude errors are measured and corrected. Any other (housekeeping) data from the GPS receiver must be telemetered to the ground via Bus-B. Once on the ground, the outputs from the receiver (i.e. signal strength, configuration status and so forth) must be converted from the format they are captured in into engineering units. This was not

possible with the software in the MOCC. To correct this shortcoming, an in-house software tool (PKTVIEW – developed by Dr. Charles Campbell of the FDAB) was updated and modified so it could be run in the MOCC. With this tool and the documentation on the receiver itself, operations personnel now have all the capabilities and insight into the GPS receiver necessary to accomplish the EO-1 mission. EO-1 GPS is now ready for the expected November 16 launch.

[Technical Contact: David Quinn]

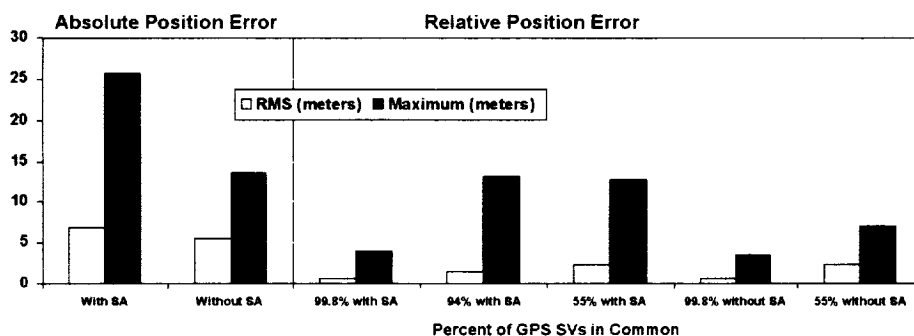
#### **4.2.5 Relative Navigation**

The goal of this task is to provide formation flying missions with a real-time capability to determine the relative positions of the individual segments by using tracking data measured from crosslinks and/or GPS.

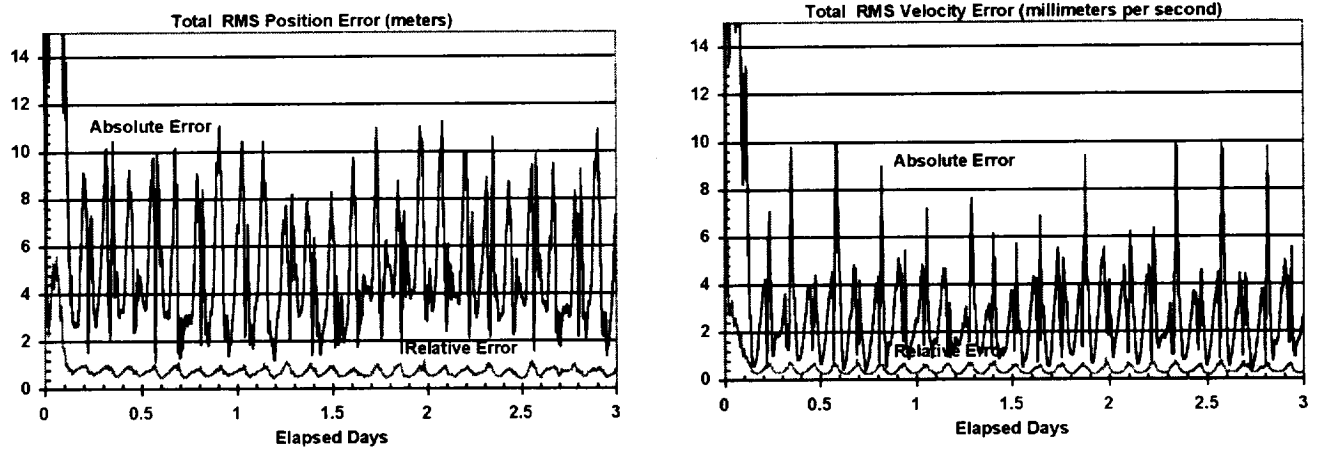
Highlights of the past year's accomplishments are:

- GEODE software modifications to allow multiple simultaneous solutions with multiple data types, to mix GPS and crosslink data; time and frequency models
- Paper presented to International Space Flight Dynamics Conference
- Implemented upgraded clock model

A paper was presented at the International Symposium on Space Flight Dynamics in Biarritz, France. This paper discusses autonomous relative navigation performance for a formation of four eccentric, medium-altitude Earth-orbiting satellites using Global Positioning System (GPS) Standard Positioning Service (SPS) and “GPS-like” intersatellite measurements. The performance of several candidate relative navigation approaches is evaluated. These analyses indicate that an autonomous relative navigation position accuracy of 1 meter root-mean-square can be achieved by differencing high-accuracy filtered solutions if only measurements from common GPS space vehicles are used in the independently-estimated solutions. Figures 4-7 and 4-8 show the position and velocity error margins.



**Figure 4-7. Absolute and Relative Steady-State Time-Wise Ensemble True Position Errors Using Filtered Solutions with GPS Measurements**



**Figure 4-8. Absolute and Relative Ensemble True RMS Position and Velocity Errors with SA Disabled Using Filtered Solutions with 99.8 percent GPS SV's in Common**

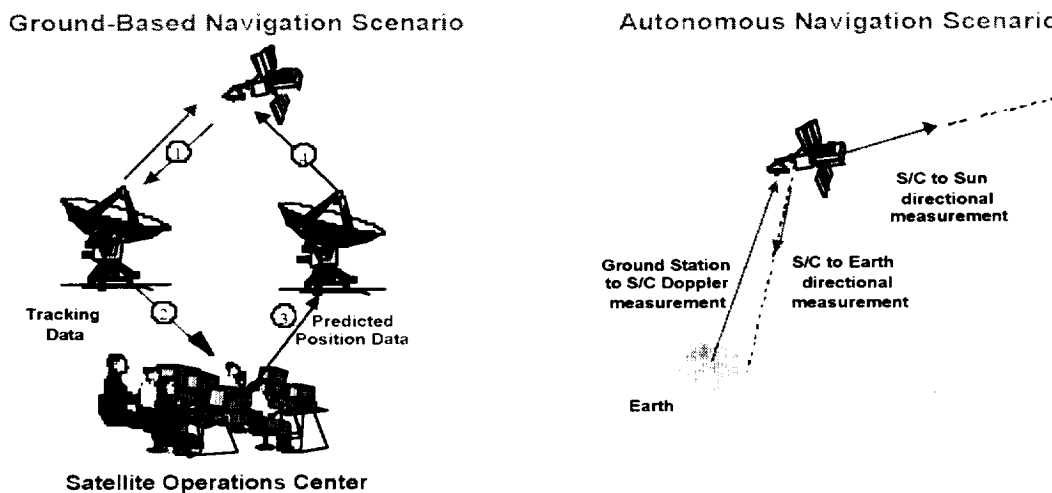
[Technical contacts: [Russell Carpenter](#), [Cheryl Gramling](#)]

#### **4.2.6 Celestial Navigation**

Celestial navigation of spacecraft opens up high earth, libration point, and deep space missions to autonomous navigation. Celestial navigation is a simulation/navigation system that uses onboard attitude sensor measurements, new algorithms, and high fidelity environmental and filter models to accurately determine the spacecraft state. Autonomous navigation has the potential both to increase spacecraft navigation system performance and success and to reduce total mission cost. Figure 4-9 shows navigation scenarios.

Highlights of the past year's accomplishments are:

- Completed Kalman filter design
- Completed analysis of ingested simulated and real spacecraft tracking and attitude data and compared to ground based solutions
- Paper presented to International Flight Dynamics Conference



**Figure 4-9. Navigation Scenarios**

[Technical contacts: [David Folta](#), [Cheryl Gramling](#)]

### **4.3 Formation Flying Technologies**

#### **4.3.1 EO-1 Formation Flying Experiment**

The formation flying requirement of EO-1 is to maintain a 1-minute separation between EO-1 and Landsat-7 with EO-1 following the Landsat-7 ground track to a tolerance of  $\pm 3$  km tolerance, approximately 6 seconds. This translates into an along-track distance of approximately 450 km with tolerance of 50 km. The mapping of this requirement into a formation flying requirement is to place a constraint on the initial separation between the two spacecraft, and maintaining that separation. Using the formation flying algorithms developed by GSFC simulations have shown that formation flying requirements can be easily met by a wide margin. By performing this spacecraft separation maintenance, pair scene comparisons between Landsat-7 and EO-1 can be made. Figure 4-10 shows two spacecraft in formation flying configuration.

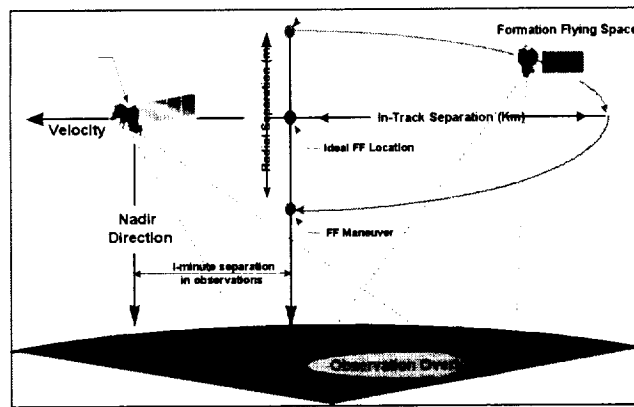


**Figure 4-10. Formation Flying**

The primary objective of enhanced formation flying is to demonstrate onboard autonomous formation flying control of the EO-1 spacecraft (using the AutoCon system) with respect to the Landsat-7 spacecraft. A secondary goal is to enable the collection of correlated science measurements and to demonstrate significantly improved space science data return through near-simultaneous observations. All algorithms must conform to AutoCon specifications in order to allow uploading during the extended mission. Individual algorithms are invoked through ground commanding of an AutoCon control mode switch.

The EO-1 maneuvers will be computed onboard under a single system architecture called AutoCon which employs separate maneuver decision/design modules or algorithms. AutoCon will control execution of the modules through an onboard mode switch, and perform constraint evaluation via fuzzy logic control.

The enhanced formation flying technology demonstration will be fully validated during the EO-1 mission. In this way, science taken during the first year with autonomous onboard formation flying control operating can be compared to previous ground operations. Likewise, operations costs with and without onboard formation flying control can also be compared. Figure 4-11 shows the observation overlaps.



**Figure 4-11. Observation Overlaps**

The core AutoCon flight control architecture required to support all enhanced formation flying (EFF) algorithms during the extended EO-1 mission was developed, integrated with the ACS, and placed onboard the spacecraft during the past year. Validation of the core AutoCon architecture will occur during the first year of EO-1 operations. The core AutoCon flight control software must be integrated with the ACS and the spacecraft prior to launch to reduce the risk and the amount of software being uploaded later in the mission. Formation flying control algorithms will be uploaded and executed under the AutoCon flight control software during the extended mission.

The AutoCon flight control system will need data from additional sensors and spacecraft subsystems such as propulsion data, ground track data, and navigation and attitude data. It will then be possible to autonomously generate, analyze, and execute the maneuvers required to initialize and maintain the vehicle formation. Because these calculations and decisions can be performed onboard the spacecraft, the lengthy period of ground-based planning, currently required prior to maneuver execution, will be eliminated. The proposed system will also be modular so that it can be easily extended to future missions. Furthermore, the AutoCon flight control system is designed to be compatible with various onboard navigation systems (*i.e.* GPS, ONS, or an uploaded ground-based ephemeris). The existing automated maneuver planning tool (AutoCon) will be modified for onboard autonomous formation flying control to demonstrate that improved science data return can be achieved by correlating nearly simultaneous data. This will be accomplished by having the flight control system plan a maneuver that places EO-1 within 1 minute of separation from Landsat-7 and then maintains that separation to a tight tolerance of 6 seconds for an extended period of time.

The EO-1 software test validation certified that all software requirements have been properly implemented and that Phase-1 of the Enhanced Formation Flying (EFF) software meets all operational objectives. The core AutoCon flight control software was qualified by executing a series of test plans, test data, and test scenarios. The results of each stage of validation was checked and documented. These activities were performed by both the developers of AutoCon and the EO-1 ACS software engineers. Quality assurance was integrated into each stage.

Technical Contacts: [David Folta](#), [David Quinn](#)

#### **4.3.2 Integration of a Decentralized Linear-Quadratic-Gaussian Control into GSFC's Universal 3-D Autonomous Formation Flying Algorithm**

A decentralized control was investigated for applicability to the autonomous formation flying control algorithm developed by GSFC for the New Millennium Program Earth Observer-1 (EO-1) mission. This decentralized framework has the following characteristics:

- The approach is non-hierarchical, and coordination by a central supervisor is not required.
- Detected failures degrade the system performance gracefully.
- Each node in the decentralized network processes only its own measurement data, in parallel with the other nodes. Although the total computational burden over the entire network is greater than it would be for a single, centralized controller, fewer computations are required locally at each node.

- Requirements for data transmission between nodes are limited to only the dimension of the control vector, at the cost of maintaining a local additional data vector. The data vector compresses all past measurement history from all the nodes into a single vector of the dimension of the state.
- The approach is optimal with respect to standard cost functions.

The current approach is valid for near time-invariant systems only. Similar to the GSFC formation flying algorithm, the extension to Linear Quadratic Gaussian (LQG) time-varying systems requires that each node propagate its filter covariance forward (navigation) and controller Riccati matrix backward (guidance) at each time step. Extension of the GSFC algorithm to non-linear systems can also be accomplished via linearization about a reference trajectory in the standard fashion, or linearization about the current state estimate as with the extended Kalman filter.

To investigate the feasibility of the decentralized integration with the GSFC algorithm, an existing centralized LQG design for a single spacecraft orbit control problem was adapted to the decentralized framework while using the GSFC algorithm's state transition matrices and framework. The existing GSFC design uses both reference trajectories of each spacecraft in formation and by appropriate choice of coordinates and simplified measurement modeling is formulated as a linear time-invariant system. Results for improvements to the GSFC algorithm and a multiple satellite formation were addressed. The goal of this investigation was to progressively relax the assumptions that result in linear time-invariance, ultimately to the point of linearization of the non-linear dynamics about the current state estimate as in the extended Kalman filter. Figures 4-12a/b represent a sample of trajectories.

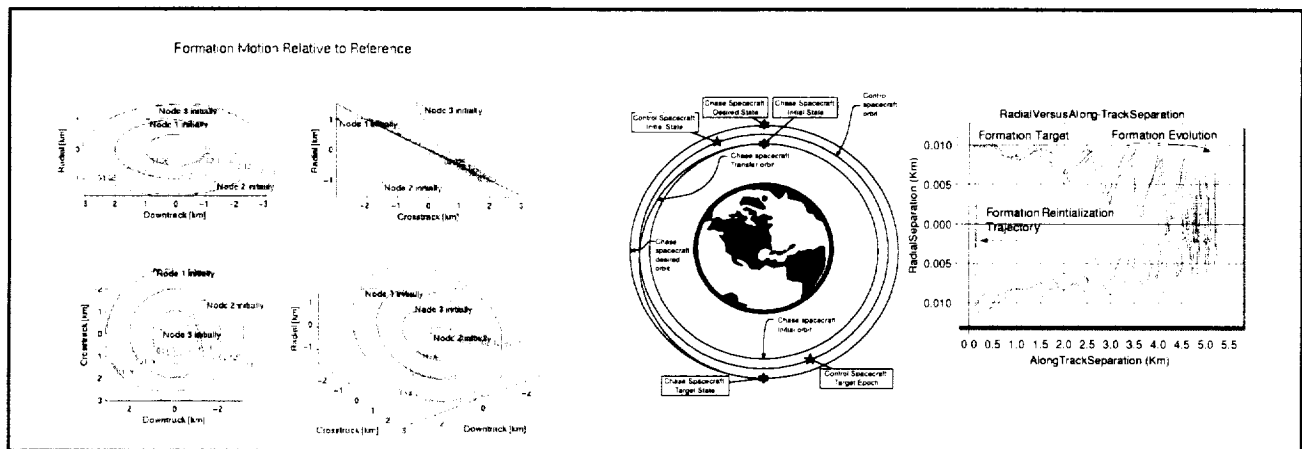


Figure 4-12a/b. Samples of Trajectories

[Technical contacts: [David Folta](#), [J. Russell Carpenter](#), [David Quinn](#)]

### 4.3.3 Tethered Formation Flying Examined for SPECS

The Sub-millimeter Probe of the Evolution of Cosmic Structure (SPECS) is a bold new mission concept designed to address fundamental questions about the Universe, including how the first stars formed from primordial material, and the first galaxies from pre-galactic structures, how the galaxies evolve over time, and what the cosmic history of energy release, heavy element synthesis, and dust formation is. Ideally, a very large telescope with an effective aperture approaching one kilometer in diameter would be needed to obtain high quality angular resolution at these long wavelengths, however this approach proves to be too expensive and therefore impractical. Instead, a spin-stabilized, tethered formation is one possible configuration being considered requiring a more advanced form of formation flying controller, where dynamics are coupled due to the existence of the tethers between nodes in the formation network. To this end an investigation into the dynamics and control of multiple tethered spacecraft systems was launched. Figure 4-13 depicts the SPECS spacecraft.



**Figure 4-13. SPECS Spacecraft**

The FDAB analysis effort was divided into three separate tasks. Task-1 involved cooperation with the Naval Research Lab in the development of the equations of motion for a rotating multi-tethered system applicable to the study of fundamental dynamic characteristics of a deep space interferometer concept. The system is assumed to be comprised of a central rigid body from which emanate  $n$ -tethered end-masses forming a symmetrical planar arrangement in the nominal configuration. The concept system is intended to execute planar rotation, to deploy and/or retract the tethered end-masses, and be capable of re-orienting the spin axis. Accordingly, the mathematical model must allow full three dimensional motion of all the constituent elements. This has been accomplished and the final report and corresponding FORTRAN model are undergoing examination.

Working with the University of Texas at Austin, Task-2 examined key linear and non-linear control methodologies which may prove applicable to the problem of tethered formation flying, specifically gain-scheduled controllers, Lyapunov based non-linear controllers and/or robust adaptive controllers. The object was to build upon the dynamic development from Task-1 in order to create a core dynamics and control model, which permits iteration and expansion while maintaining the primary thrust of the tethered formation. The ultimate goal for this task was to develop a set of control laws centered on the core model from Task-1. This will serve as a first order tool for examining the dynamics and control of a variety of design configurations.

Finally, the main objective of Task-3 was to cooperate with personnel from Payload Systems Inc. to examine possible configurations using the Generalized Information Network Analysis (GINA) framework developed at the Massachusetts Institute of Technology and conduct preliminary configuration trade studies. Here trades such as reel-in-rate versus rotation rate versus aperture diameter were considered as well as angular momentum management and re-targeting and rotation rate versus aperture diameter versus tether tension. Many possibilities were examined in an effort to conduct a "broad-brush" analysis to get a high level understanding of the issues involved with each as well as understand the favorable regions in the trade space. This work has been of immeasurable help by providing insight into the most likely design parameters for this complex spacecraft system. As the configuration trades narrow the trade space, the dynamics and control models of Tasks-1 & 2 will be employed to evaluate the overall feasibility of large multi-tethered spacecraft formation for interferometric and/or large aperture science missions such as SPECS. While detailed design work is expected to take years, this is seen as a crucial first step to making such mission a real possibility.

[Technical contact: [David Quinn](#)]

## **4.4 Attitude Determination and Modeling Techniques**

### **4.4.1 SKYMAP**

**Completion of the SKY2000 Version 3 Master Catalog (MC).** The delivery of SKY2000 Version 3 MC in June of 2000 marked the global replacement of the Henry Draper (HD) spectral type data in the SKY2000 catalog, along with the global replacement of the photovisual (*pv*) and photographic (*ptg*) magnitude data. Access to the improved spectral and magnitude data in the MC resulted in a significant improvement in magnitude estimation capability for mission star catalog generation. The SKY2000 Version 3 MC now contains 299,160 entries, an increase of 61 over the 299,099 entries in SKY2000 Version 2. SKY2000 Version 3 contains 273,202 photovisual magnitudes (an increase of 62,280 or 29.5% from Version 2) and 255,362 photographic magnitudes (an increase of 73,078 or 40.1% from Version 2). Many other individual corrections to MC data were also made during this period.

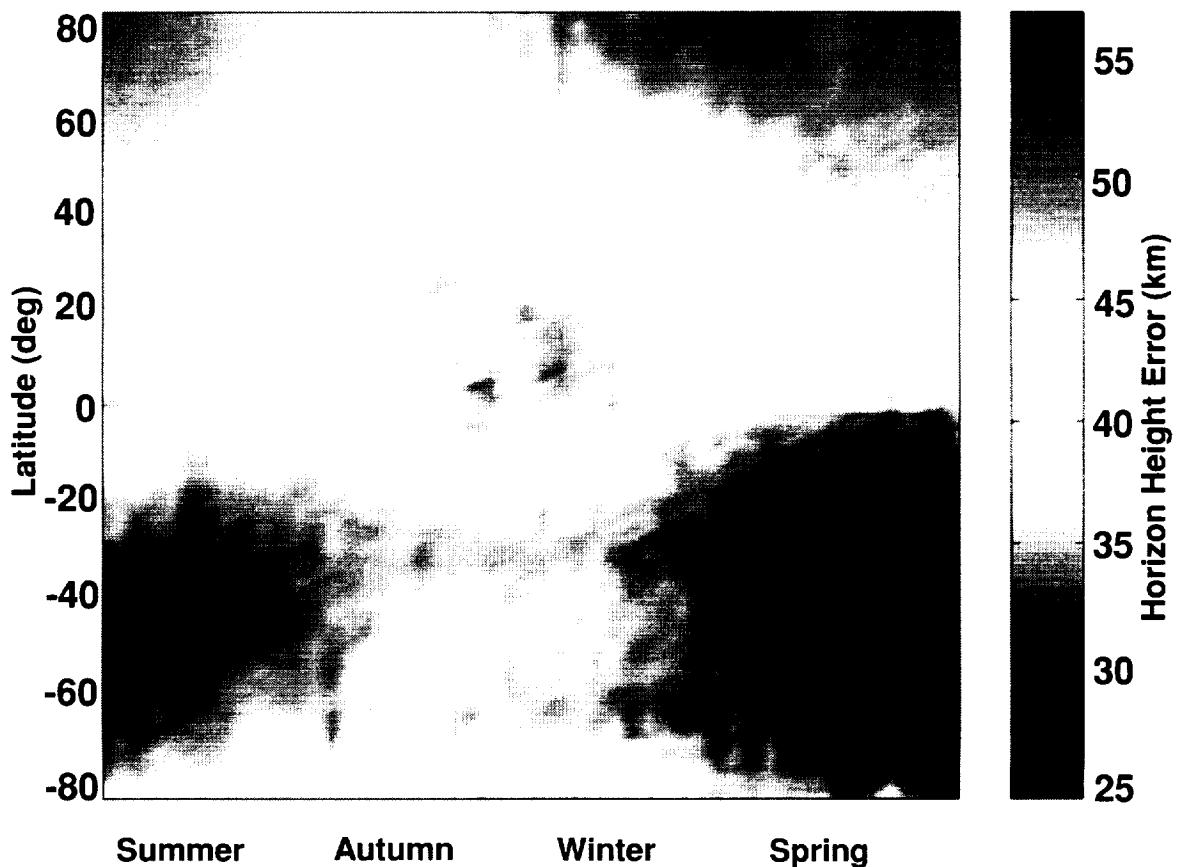
**Run Catalog Consultation.** The FDAB provided star catalog consultation for several current and future missions including: MAP (Run Catalog checklist, 11/99; catalog requirements meeting, 01/00), Terra (CT-601 performance analysis, 12/99), VCL (Run Catalog generation, 02/00), Landsat-7 (Run Catalog content discussion and generation, 03/00), and R-XTE (OBC catalog analysis and update).

**General SKYMAP Consultation.** General information and support was provided to GSFC Projects, Universities, and other external users of the SKY2000 MC data and products. Some examples of partnering during this fiscal year include: Lockheed-Martin (flux to magnitude conversion algorithms, 04/00), U. Texas (Austin; radial velocity data & availability, 05/00), SOHO Run Catalog Generation (11/99), Landsat-7 Run/Supplemental Catalog Generation (06/00).

[Technical contact: [David Tracewell](#)]

#### **4.4.2 Attitude Sensor Performance Analysis**

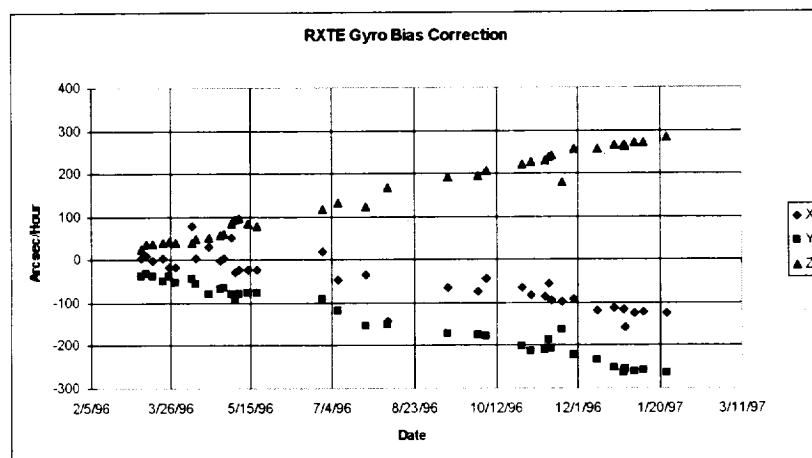
For this fiscal year horizon radiance modeling was studied as well as gyro modeling from mission experience. Using TOMS data, the following horizon radiance modeling data was obtained (Figure 4-14). Variations in colors/shades correspond to horizon height errors related to latitude and month.



**Figure 4-14. Horizon Radiance Modeling**



Long-term gyro performance for a variety of missions was also evaluated over the past year. The results of this analysis indicate a long term linear change in biases. An example of this trend can be seen in gyro data from the Rossi X-Ray Timing Explorer (RXTE) (figure 4-15):

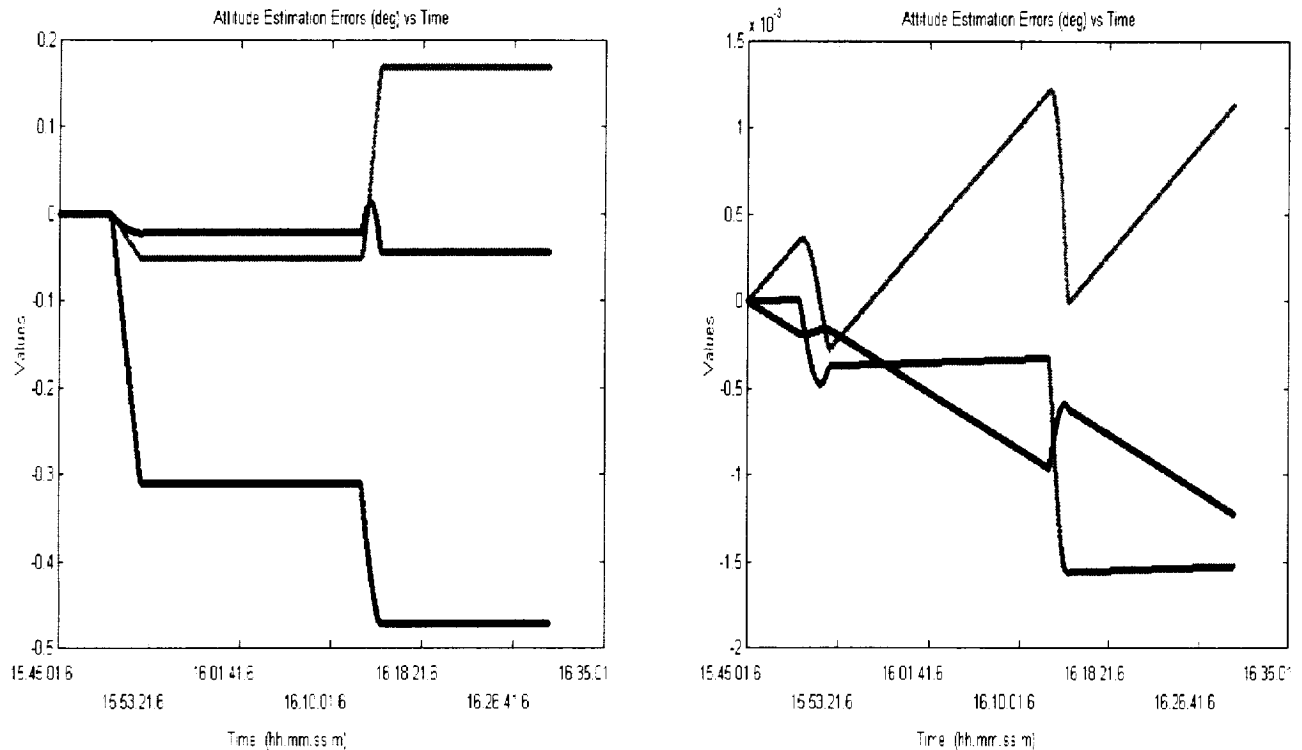


**Figure 4-15. Gyro Performance**

[Technical contact: [Rick Harman](#)]

#### **4.4.3 Advanced Attitude Determination and Sensor Calibration Techniques**

A new gyro calibration utility was developed which has proven to be faster and more accurate. The old algorithm involved estimating attitudes before and after each maneuver followed by combining that data with the spacecraft gyro data in another algorithm to estimate the gyro parameters. This proved to be a cumbersome process with very little flexibility. A new process was developed this year to estimate the attitude and gyro parameters in one utility. Besides the timesavings involved in only running one utility, the ability to include non-sequential batches of data has been included. Thus, more batches of data from a variety of different times can be included in the estimation process allowing for greater observability of the estimation parameters. This utility has been flight tested on both the TERRA and WIRE data. The WIRE gyro in particular demonstrates what gyro calibration can do for a mission. Figure 4-16 demonstrates the typical attitude propagation errors though maneuvers before and after gyro calibration:



**Figure 4-16. Attitude Propagation Errors Before (left plot) and After Gyro Calibration (right plot)**

The overall RSS error at the end of the maneuvers was 0.5 degrees before calibration and 0.0024 degrees (9 arc-seconds) after calibration with the new utility.

In addition, GNCC was directed to assist in reconstructing the HST rate profile during its gyro failure, which occurred 5 weeks before a shuttle-servicing mission. The gyro failure mode known as "Zero Gyro Mode" consisted of pointing the HST z-axis at the Sun using Sun sensors and inducing a small rotation rate about the z-axis. During orbit night all actuator commands are disabled, and the spacecraft drifts with the Sun line rotation providing some dynamics rigidity. The goal is to keep the spacecraft z-axis close to the Sun line when HST enters orbit day. The results shown in Figure 4-17 were obtained using HST magnetometer, reaction wheel, torquer bar, and remaining gyro data.

The y-axis of the plot contains the estimated rate in degrees/second, and the x-axis is in seconds. The orbit night periods can be picked out in the above plots by looking at the negative peaks in the rates. During orbit night the spacecraft is rotating about the z-axis with an approximate constant rate with actuators being turned off. When the computed rate was compared to the rate from the remaining gyros, an excellent fit was obtained.

[Technical contact: [Rick Harman](#)]

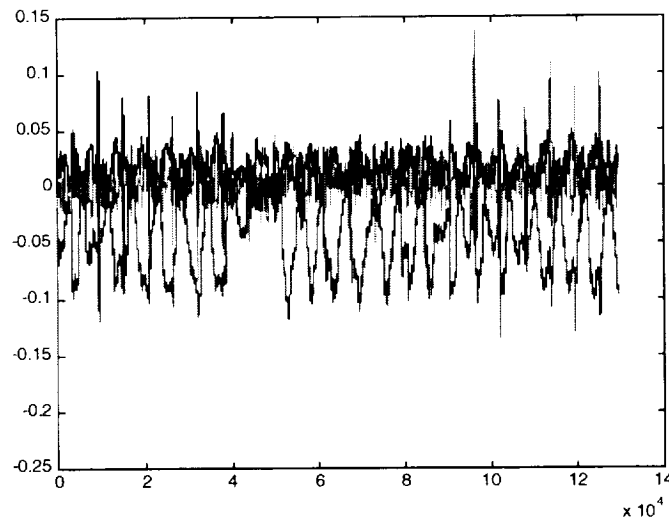


Figure 4-17. HST Estimated Rates Using Only Magnetometer and Sun Sensor Data

## 5.0 Branch Infrastructure

### 5.1 Flight Dynamics Tool Program

Flight dynamics analysis services can only be provided with a suite of specialized analytical tools. The branch currently uses a large complement of commercial and in-house developed software tools. Missions such as LISA, Marsat, MAXIM, Constellation X, GEC, MMS and Leonardo continue to drive the need for improved modeling and computational techniques. Thus, the tools program provides a means of *enabling* new missions.

The majority of the effort in the Flight Dynamics tools program supports the development and enhancement of software tools for advanced mission planning activities. Flight Dynamics Tools activities are conducted in direct response to customer (Earth Sciences Enterprise, Space Sciences Enterprise, Human Exploration and Development of Space Enterprise) requirements. These tools are required in support of all aspects and phases of mission formulation, design, implementation, and operations. These tools are also required in support of the flight dynamics technology development activities associated with the Flight Dynamics Analysis Branch. Newly developed tools are also used in the Goddard Integrated Mission Design Center (IMDC). Thus, the tools program performs the following:

- Implementation of new computational techniques in existing mission planning and analysis tools
- Development of new mission planning and analysis tools (based on needs identified for future missions)
- Error correction
- Configuration control of FDAB tools

The institutional software tools used by the Flight Dynamics Analysis Branch are upgraded to use results of various technology initiatives in order to improve capabilities and responsiveness to the Earth Science and Space Science customers. An example is the research into dynamic system theory for improved trajectory targeting capability. This and other basic research is supported through the SOMO technology program and cross enterprise programs.

The FDAB tools program requires contractor services to assist with software configuration control. Support is also provided to commercialization efforts. This includes packaging of software approved for external licensing. Currently, software available for licensing includes:

- Goddard Trajectory Determination System (GTDS)
- Attitude Determination Error Analysis Systems (ADEAS)

- Orbit Determination Error Analysis System (ODEAS)
- Swingby Trajectory Design Program (SWINGBY)
- General Maneuver Program (GMAN)
- Multimission Three-Axis Stabilized System (MTASS)
- Multimission Spin-Axis Stabilized System (MSASS)
- GPS Enhanced Orbit Determination (GEODE)
- Elements Conversion Program (ELCONV)
- Guide Star Occultation Utility (GSOC)

[Technical Contact: Thomas Stengle]

## **5.2 GNCC Flight Dynamics Data Lab**

The Flight Dynamics Lab completed its initial configuration during FY2000. This lab is used for the development, test, integration, and operation of software systems as well as analysis for the performance of flight dynamics functions for operational and new missions. Installation of servers and migration of branch personnel was completed. Several new computers were installed. In addition to the servers, the lab now houses two Sun Ultra 60 workstations, two HP workstations, 6 Dell dual processor workstations, an online storage device with approximately 700GB of usable storage as well as printers, scanner, overhead projector, voice and video equipment. Branch commercial software licenses are now managed by the servers and the online storage device provides the users with regular tape backup capability. Addition of this equipment enabled FDAB personnel to do advanced mission analysis, mission system prototyping and test. The CGRO Re-entry was supported using two of the Dell machines and the TRIANA mission maneuver planning is scheduled to be supported from the lab. The TRMM dynamics simulator was transferred to the FD Lab. The FD Lab also houses the on-line documentation server and the GNCC and Branch WEB page servers.

The FD Lab provided consultation to the GNCC Information Technology Security Officer (ITSO) for security configuration and monitoring. The lab security plan will be used as a model for the other area within GNCC.

Plans for the coming year call for the FD Lab to implement a wireless network capability, upgrading the internal lab network and testing of upgraded operating systems and networking configurations. The FD Lab will also provide voice lines for the Expedition One support.

[Technical contact: Sue Hoge]

## **5.3 Branch Library**

During FY00, the FDAB implemented a new online technical library. This library uses the commercial tool Docushare, which is a web based tool that can catalog, store, search and access a wide variety of files. Initially, the library was populated with various document files created over the last several years, which contain technical reports from various branch technology research activities, presentation slides from many spacecraft project technical reviews, and software documentation. The library continues to be expanded and will contain all future analysis reports, future mission studies, software specifications and control system documentation created by the branch. General spacecraft reference documentation will also be placed in the library to enable branch engineers to quickly access spacecraft information during anomaly investigations. Access to the library is controlled to protect proprietary and International Traffic In Arms Regulation (ITAR) restricted data. In the future, the library will also contain selected flight data.

[Technical Contact: Catherine Waltersdorff]

## **5.4 Employee Handbook**

The initial draft of the FDAB Employee Handbook was completed. Authored by more than a dozen members of the FDAB staff, the purpose of the handbook is to document for all branch employees a standard set of procedures for supporting flight projects, future mission analysis activities and technology projects. The handbook also clearly documents various administrative procedures important to the branch (for example, procedures for technical paper approval).

While not yet complete, future updates to the document in FY01 will include detailed technical guidelines for control system design and trajectory design. The handbook will also capture flight dynamics “best practices.”

[Technical Contact: Thomas Stengle]

## **6.0 Interagency Activities**

### **6.1 GSFC Standards Program**

The FDAB supports the GSFC standards program and the Consultative Committee for Space Data Systems (CCSDS).

The GSFC standard program aims to expand the scope of best practices, and to develop an agency-endorsed database of preferred technical standards for NASA

The Consultative Committee for Space Data Systems (CCSDS) is an international organization of space agencies interested in mutually developing standard data handling techniques, to support space research conducted exclusively for peaceful purposes.

The CCSDS Sub-Panel P1J is specifically chartered to investigate and recommend Navigation Data standards. P1J has a membership representing several international agencies. The work of P1J is accomplished primarily at workshops, conducted at least twice a year, at facilities coordinated by the hosting member agency. The main task of P1J is to generate documents defining the preferred standards for the exchange of navigation data. The latest workshops were conducted at Annapolis, Maryland, in May, and at the European Space Agency (ESA) Vilspa facility, Spain, in October.

Currently P1J is working on a green book, for navigation definitions and conventions, with projected completion on December 2000. Response to the CCSDS Proximity-1 Space Link Protocol, Red Book, will be provided through a red book, generated by P1J, providing recommendations for navigation data exchange in support of proximity operations. New CCSDS red books on recommendations for orbit, tracking, attitude, proximity ops, environmental models and astrodynamics constants will be developed in the future.

For information about CCSDS and the GSFC standards program please refer to <http://www.ccsds.org/> and <http://joy.gsfc.nasa.gov/GTSP/>

[Technical contact: Felipe Flores-Amaya]

### **6.2 Mars Climate Orbiter Mishap Investigation**

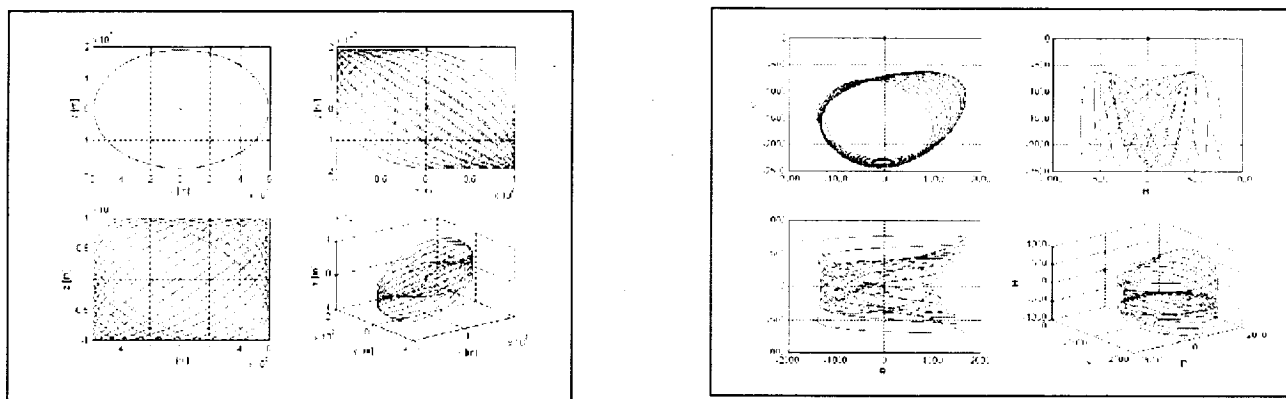
A service provided by the Flight Dynamics Analysis Branch is to support the peer reviews and investigation reviews of missions. Last year the Mars Climate Observer (MCO) unfortunately failed in its Mars mission due to an underlining unit conversion error. As part of the MCO mishap board, the FDAB supported the investigation by providing leadership in the trajectory design, navigation, and control areas. The FDAB participated in the MCO Mishap board with the MSFC Center Director, NASA HQ, and independent individuals. The findings for this mishap were released under a document that not only provided information regarding the mishap, but also established new guidelines for future NASA mission. It detailed the expectations of all future missions with respect to mission success. The findings addressed the use of faster, better, cheaper in the context of mission success and mission safety. Copies of this document can be obtained through NASA HQ.

[Technical contact: David Folta]

## **7.0 Outreach Activities**

### **7.1 Educational Outreach: International Space University**

A part of the FDAB effort for educational outreach, a student of the International Space University (ISU) was selected to participate in analysis with the FDAB in order to fulfill his requirements for a Masters degree. A part of his 10-week effort, a Matlab demonstration tool was developed to study formation-flying concepts at the L1 LaGrange point. The student, Mr. Christoph Wagner of Germany, completed an initial investigation that included libration orbit generation, linear Quadratic Regulator controls, and formations. A sample of his Matlab work appears in Figure 7-1a/b.



**Figure 7-1a/b Libration Orbit Control, About an Orbit and Relative Motion**

[Technical contact: [David Folta](#)]

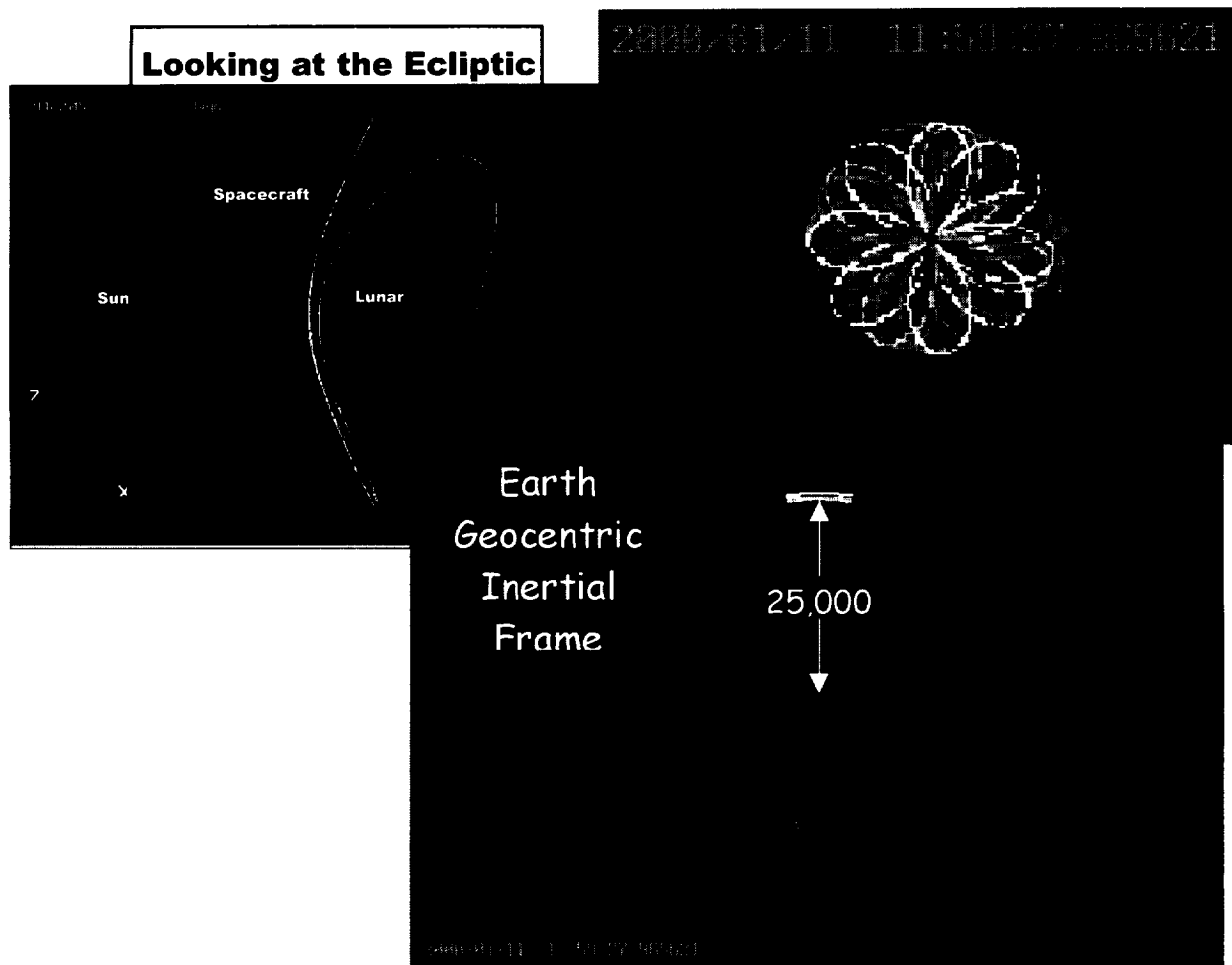
### **7.2 SAMPEX University Operations**

The University of Maryland Aerospace Engineering Department completed its first full year of sole responsibility for flight dynamics support of the Solar Anomalous and Magnetospheric Particle Explorer (SAMPEX) spacecraft. In this role, a team of University of Maryland undergraduate and graduate students provides routine spacecraft orbit determination, attitude determination, attitude sensor analysis, and flight dynamics product generation. This effort is sponsored and supported by the FDAB, which provides consultation support as needed and periodically reviews the overall program status. This has been a very successful outreach initiative and gives the student team practical experience and training in spacecraft flight dynamics computations, the use of several commercial ground support tools and analysis of flight data. The operation also serves as a test bed for researching ground system automation techniques. During the past year, new team members were successfully trained following some losses due to graduation. Some members of the team that have graduated have taken jobs in private industry supporting spacecraft operations. This is another measure of success for the program.

[Technical Contact: [Tom Stengle](#)]

### **7.3 Educational Outreach: NASA Academy**

As part of the GSFC outreach effort to support universities, the FDAB took part in the NASA Academy, a summer internship for undergraduate and graduate students who are considered tops in their field. This year the FDAB hosted two students, Ms. Corissa Young from Colorado and Mr. Adam Ross from Harvard. Their subject was to complete mission design concepts for Unique Non-Keplerian orbits. This cooperative work was enabled under a director's discretionary fund for advanced research topics. The work covered 10 weeks during the summer with final results presented to a GSFC peer review panel. An example of their efforts is shown in figure 7-2, the orbits of a vertical libration orbit and Earth polar sitters that enable continuous viewing of the Earth's polar regions.



**Figure 7-2. Vertical Libration Orbit and Earth Polar Sitters**

[Technical contact: [David Folta](#)]

#### **7.4 PREST Program**

During FY00, the FDAB supported two students under a grant with the George Washington University Program of Research and Education in Space Technology (PREST). One of these students is currently in residence at the GSFC and is working with branch members on research of formation flying control techniques. The other student completed analysis of new algorithms for attitude determination and rate estimation using GPS measurements.

[Technical Contact: [Tom Stengle](#)]

#### **7.5 Graduate Student Research Program (GSRP)**

The FDAB continued its long standing support of the GSRP program. In FY00, one GSRP sponsorship came to a close, while two new GSRP efforts were initiated:

- "Decentralized Control of Distributed Satellite Networks" to be performed by Mr. Belanger of UCLA
- "Feasibility of Atmospheric Penetration for Satellite Formation Flying Experiment" to be performed by Mr. Joseph Schultz of the University of Maryland

[Technical Contact: [Tom Stengle](#)]

## **7.6 Public Education/Community Outreach**

The following outreach activities were supported in FY00:

### **Science Fair & Engineering Judging**

- District of Columbia Citywide Science Fair, Howard University, WDC, 3/19/00

### **Rocket Building/Engineering Design Projects**

- Take Our Daughters to Work Program, Egg Drop Contest, NASA GSFC, Greenbelt, MD, 4/14/00

### **Career Presentations**

- University of Maryland Department of Aerospace Engineering Sigma Gamm Tau Chapter
- National Academy of Science, Women in Science and Engineering (WISE) Committee, WDC 10/30/99
- Joint Education Facilities, 2574 Naylor Road, SE, WDC, 1/8/00
- Tarrant County College, "Careers in Science & Tech. – A-A Contributions to Tech.", Ft. Worth, TX, 2/7/00
- PG Community College, Science Engineering Education Day, 301 Largo Rd, Largo, MD, 2/1/00
- QEM/MSE National Conference, "You meet the Scientist", JW Marriott Hotel, WDC, 2/12/00
- Jeremiah E. Burke High School, 60 Washington St., Dorchester, MA, 3/10/00
- The Stone Ridge School, School of the Sacred Heart, 9101 Rockville Pike, Bethesda, MD, 3/13/00
- Ferrebee Hope Community School, 3999 8<sup>th</sup> St., SE, WDC, 3/20/00
- GW Univ., Women & Power Leadership Program, Mt. Vernon Campus, WDC, 4/20/00
- DC Metropolitan Organization of Scientists, Bolling AFB, WDC, 9/12/00
- Trenton & Plainville HS, Rutgers Campus, Piscataway, NJ, 7/20/00

### **Career Day Presentation**

- NTA Scientist and Engineer School Visitation Day, Kingsford, ES, Mitchellville, MD 11/4/99

### **Speech (Open, Award, Closing & Graduation Ceremonies, Luncheon)**

- National School Boards Association, The Education Technology Program, Dallas TX, 11/12/99
- Zonta International Club of Charles County, "Flying into the new millenium", Charles County, MD, 1/11/00
- NCA&T, Ronald McNair Memorial Program, Greensboro, NC, 1/28/00
- Tarrant County College, Luncheon, Ft. Worth, TX, 2/7/00
- National Academies' 2000 African American History Day Program, WDC, 2/14/00
- Defense Information Systems Agency, Women's History Month-Kickoff, Arlington, VA, 3/8/00
- US Department of Veteran's Affairs, Women's History Month, 810 Vermont Ave., NW, WDC, 3/14/00
- Grant County All Academic Team Dinner, Grant IN, 5/20/00
- Richard Montgomery H. S. Graduation-Rockville, MD, Constitution Hall, WDC, 6/8/00
- Tech 2000 Symposium, Breakfast Keynote Speaker, Eden Roc Resort, Miami FL, 7/21/00
- Tuskegee Airmen's National Convention, Youth Luncheon, San Antonio, TX, 8/10/00
- Rutgers University, Off.Min.Under.Prog. Freshman Orientation, Piscataway, NJ, 8/20/00
- Minority Access National Role Models Conference, Washington Marriott, WDC, 9/17/00

### **Program Visits NASA GSFC/Mentor Student/Fellow**

- MIE, Faculty visit, setup by NASA HQS, 10/21/99
- Sunbeams Program, St. Frances Xavier MS, Greenbelt, MD, 1/13/00
- Delta Academy Baltimore, A-A Girls mentoring program, Greenbelt, MD, 2/17/00

### **Education/Career Conference or Panel**

- National Academy of Science WISE Committee, WDC 10/30/99
- Department of Defense (DoD) Leaders of Educ. Programs w/ SME Dimensions Conference, Doubletree Hotel Arlington, VA 11/5/99
- QEM/MSE Natl Conf., "Career Pathways for Ph.D.'s ...", JW Marriott Hotel, WDC, 2/12/00
- NAFFEO's Annual Black College Student's High Tech Expo, Hilton Hotel and Towers, WDC, 2/15/00
- Penn State, Math Options Day, Erie, PA, 5/9/00
- Women's Information Network, National Democratic Club, WDC, 6/1/00



- MIT Mites 25<sup>th</sup> Anniversary Conference, MIT Sloan Bdg, Cambridge, MA, 7/15/00
- Tech 2000 Symposium, Women's History & Issues in Science & Technology, Miami FL, 7/22/00
- Congressional Black Caucus, "Chic Geek on Cyberstreet", WDC, 9/15/00

#### **Online/Video Conference Interactive Session**

- Women of NASA (WON) Chatline, NASA GSFC, MD, 2/2/99, 2/25/00
- Network Resources and Training Sites (NRTS) Program, South Carolina State Univ., Video conference, 6/12/00
- "Digital Diversity: Power to the People?", Videoconference WHUT TV 32, Howard University, 10/27/99
- Minority University - Space Interdisciplinary (MU-SPIN) Space Mission Involvement Workshop
- Videoconference, Morgan State University, 12/10/99 (Ref. <http://nasa.utep.edu/miwc/>)

#### **External Advisor/Mentor**

- Howard University, Graduating Senior Architectural Student: Rodney Lapson, Thesis: Moon Base.

#### **Television/Radio/Magazine/Website Interviews**

- NBC Nightly News, "Women to Watch", Andrea Mitchell, 1/13/00
- iVillage.com, "Women Who Rule", 2/00
- NSBE Engineer, Malik Russell, 2/3/00
- Spacekids.com, Denise Jewell, 2/3/00
- ScienceMaster.com, "Meet Dr. Aprille Ericsson-Jackson", Gene Mascoli, 3/00
- The George Lucas Foundation, Edutopia: "Bridging the Digital Divide", Spring 2000, Sara Armstrong Essence Magazine, "Ya Done Good Girl", 5/00
- Yahoo Internet Life, "How America Uses the Net", Jeremy Kaplan, 212-503-5167, 9/00
- Howard University Magazine, Martha Frase-Blunt, 703-683-5658, 9/00
- Woman Engineer, "To Give is to Receive", Anne Baye Eriksen, 10/00

#### **Committees**

- NASA GSFC: Black History Club, NTA GSFC Chapter-President, Diversity and Recruitment Team; National Technical Association; National Conference Planning Committee, National School Visitation Committee Chair, Publications and Editorial Committee; Building STEPS Board Member.

#### **Proposal/Application Reviewer**

- Graduate Student Researchers Program, NASA GSFC, Code 160, Greenbelt, MD 20771, 3/00
- National Science Foundation (NSF) Undergraduate Engineering Education, Arlington, VA, 3/00

[Technical contact: [Aprille Ericsson- Jackson](#)]



## **Appendix A–Awards**

List of awards earned in FY2000:

Earth Observing System-AM Project Team 2000

GEODE was a runner-up in NASA's Software of the Year competition.

Group Achievement Award, Customer Service Excellence Award Microwave Anisotropy Probe (MAP) Flight Software Team, February 9, 2000

Group Achievement Award, Quality and Process Improvement Annual Award Microwave Anisotropy Probe (MAP) Simulation Team, October 15, 1999

Group Achievement Award, Quick Scatterometer (QuikSCAT) Observatory and Mission Operations Team, August 14, 2000

GSFC Annual Moe I. Schneebaum Memorial Award for Engineering was given to David Folta

GSFC Award of Merit was given to Robert L. DeFazio for support to numerous Earth and space science flight projects

GSFC Certificate of Appreciation to the CGRO Re-entry Team

GSFC Outstanding Mentor Award was given to David Mangus

GSFC Performance Awards to the FDAB CGRO Re-entry Team

GSFC Quarterly Customer Service Excellence Award to the MAP Maneuver Team

GSFC Quarterly Outstanding Teamwork Award to the EOS AM Project Team

GSFC Quarterly Outstanding Teamwork Award to the Terra Flight Dynamics Team

GSFC Special Act Awards to the FDAB CGRO Re-entry Team

NASA Academy Certificate of Recognition was given to David Folta

NASA Group Achievement Award / Center of Excellence for Lunar Prospector Support

NASA Group Achievement Award /Mars Climate Orbiter Mishap Investigation Board, Achievement Award via MSFC Director

Outstanding Teamwork Group Award to the IMDC team

Terra Flight Dynamics Team 2000

## **Appendix B—University Grants**

The following university grants being administered by FDAB engineers were in place in FY00:

1. GRANT NAG5-9961 with the University of Maryland Department of Aerospace Engineering titled “Precise Virtual Rigid Body Control of a Satellite Constellation.” This grant is developing a possible control strategy for formation flying.

[Technical Contact: Thomas Stengle]

2. GRANT NAG5-9890 with the University of Maryland Department of Aerospace Engineering titled “Rarefied Flow Aerodynamics for Stability and Control of Formation-Flying Satellites.” This grant is researching problems and control strategies for spacecraft flying in formation with low perigee passes. This research may benefit the development of control approaches for the Geospace Electrodynamics Connections (GEC) mission.

[Technical Contact: Marco Concha]

3. GRANT NAG5-8697 with the University of Colorado at Boulder titled “Algorithms for Autonomous Orbit Determination and Formation Flying.” The focus of this grant is on algorithms for use of GPS for formation flying missions in highly elliptical orbits, including signal acquisition and tracking and relative navigation.

[Technical Contact: Steve Hughes]

4. GRANTS NAG5-8694 and NAG5-8879 with the University of California at Los Angeles titled “Decentralized Estimation and Control of Distributed Spacecraft,” and “Precise Relative State Estimation and Control of Distributed Satellite Networks.” These grants are developing and applying new decentralized control architectures for satellite formations.

[Technical Contract: Russell Carpenter]

5. GRANT NAG5-9829 with the University of Texas at Austin titled “Spacecraft Rendezvous Navigation with Integrated INS-GPS.” This grant is focusing on GPS/INS software architecture development for relative navigation and attitude determination.

[Technical Contract: Russell Carpenter]

6. GRANT NAG5-9612 with Cornell University Sibly School of Mechanical and Aerospace Engineering titled “New Algorithms for Magnetometer Orbit and Attitude Estimation.” This grant is studying the feasibility of a moderate precision navigation (<10 km orbit, <0.5 degrees attitude) using Magnetometer data.

[Technical Contract: Richard Harman]

7. GRANT NAG5-9748 with Princeton University Department of Mechanical and Aerospace Engineering titled “Satellite Attitude Estimation with the Two Step Optimal Estimator.” This grant is studying the ability of the two-step algorithm to out perform the standard Extended Kalman Filter currently used for spacecraft and ground attitude estimation.

[Technical Contract: Richard Harman]

8. GRANT NAG5-8770 with Technion-Israel Institute of Technology Department of Aerospace Engineering titled “Improvement of the REQUEST Attitude Determination Algorithm for Aiding MAGNAV.” This grant is studying the possible advantages of using the Recursive QUEST algorithm in place of the pseudo-linear and extended Kalman Filters in the real-time Magnetometer Algorithms.

[Technical Contract: Richard Harman/572]

## **Appendix C–Conferences and Papers**

List of conferences and professional papers in FY2000:

- Lauri K Newman, Paul J. Noonan, and Cheryl J. Gramling, "Ground System Support Of An Onboard Navigation System: Implementation And Operations Experiences", AAS 00-121. AAS/AIAA Space Flight Mechanics Meeting, Clearwater, FL, January 23-26, 2000.
- G. Lightsey, C. Campbell, R. Carpenter, J. Simpson, G. Davis, "Design and Performance of Space Algorithms for the GPS Receiver used on International Space Station and Crew Return Vehicle," Proceedings of the International Workshop on Aerospace Applications of the Global Positioning System, Jan 31-Feb 2, 2000, Breckenridge, CO.
- F. Bauer, J. Bristow, R. Carpenter, J. Garrison, K. Hartman, A. Long, T. Lee, D. Kelbel, V. Lu, J. How, F. Busse, P. Axelrad, M. Moreau, "Enabling Spacecraft Formation Flying in Any Earth Orbit Through Spaceborne GPS and Enhanced Autonomy Techniques," Proceedings of the International Workshop on Aerospace Applications of the Global Positioning System, Jan 31-Feb 2, 2000, Breckenridge, CO.
- R. Carpenter, "A Preliminary Investigation of Decentralized Control for Satellite Formations," Proceedings of the 2000 IEEE Aerospace Conference, Mar 18-25, 2000.
- A. Long, D. Kelbel, T. Lee, R. Carpenter, C. Gramling, "Autonomous Relative Navigation for Formation-Flying Satellites Using GPS," CNES 15th International Symposium on Space Flight Dynamics, June 26-30, 2000, Biarritz, France.
- A. Long, D. Kelbel, T. Lee, R. Carpenter, J. Garrison, "Autonomous Navigation Improvements for High Earth Orbiters Using GPS," CNES 15th International Symposium on Space Flight Dynamics, June 26-30, 2000, Biarritz, France.
- R. Carpenter, D. Folta, C. Wagner, "Formation Flying with Decentralized Control in Libration Point Orbits," CNES 15th International Symposium on Space Flight Dynamics, June 26-30, 2000, Biarritz, France.
- Cheryl Gramling, "Preliminary Operational Results of the TDRSS Onboard Navigation System (TONS) for the Terra Mission", June 2000, ISSD conference, Biarritz, France.
- Lauri K. Newman, Richard J. McIntosh, and Paul J. Noonan, "Terra Ascent Planning to Meet Landsat-7 Phasing Requirements," AIAA 2000 -4342, AIAA Astrodynamics Specialist Conference, Denver, CO, August 14-17, 2000.
- Julie Deutschmann, Itzhack Bar-Itzhack, and Rick Harman, "A LEO Satellite Navigation Algorithm Based on GPS and Magnetometer Data", International GPS Workshop & International Flight Dynamics Conference, Biarritz, France.

## **Appendix D–Acronyms and Abbreviations**

This appendix gives the definitions of acronyms used in this document.

|       |   |
|-------|---|
| AAS   | American Astronautical Society                    |
| ACS   | Attitude Control System                           |
| ACT   | Attitude Control Thrusters                        |
| AETD  | Applied Engineering and Technology Directorate    |
| AI    | Artificial Intelligence                           |
| ALI   | Advanced Land Imager                              |
| AO    | Announcement of Opportunity                       |
| APL   | Applied Physics Laboratory                        |
| AST   | Autonomous Star Tracker                           |
| ATMS  | Advanced Technology Microwave Sounder             |
| CCSDS | Consultative Committee for Space Data Systems     |
| CETDP | Cross Enterprise Technology Development Program   |
| CGRO  | Compton Gamma Ray Observatory                     |
| COTS  | Commercial Off-the-Shelf                          |
| CPT   | Comprehensive Performance Test                    |
| CSOC  | Consolidated Space Operations Contract            |
| CVS   | Concurrent Version System                         |
| DACC  | Distributed Active Archive Center                 |
| DoD   | Department of Defense                             |
| DSN   | Deep Space Network                                |
| DSS   | Digital Sun Sensor                                |
| DST   | Dynamical Systems Theory                          |
| EFF   | Enhanced Formation Flying                         |
| EMOS  | EOS Mission Operations System                     |
| EO    | Earth Observing                                   |
| EOS   | Earth Observing System                            |
| ESA   | European Space Agency                             |
| ESSP  | Earth System Science Pathfinder                   |
| EUVE  | Extreme Ultraviolet Explorer                      |
| FAA   | Federal Aviation Administration                   |
| FDAB  | Flight Dynamics Analysis Branch                   |
| FDS   | Flight Dynamics System                            |
| FDSS  | Flight Dynamics Support System                    |
| FDF   | Flight Dynamics Facility                          |
| Flex  | Fluorescence Experiment                           |
| FOT   | Flight Operations Team                            |
| FSW   | Flight Software                                   |
| FY    | Fiscal Year                                       |
| GEO   | Geosynchronous Earth Orbit                        |
| GEODE | GPS Enhanced Orbit Determination Experiment       |
| GEONS | GPS-Enhanced Orbit Navigation System              |
| GINA  | Generalized Information Network Analysis          |
| GNCC  | Guidance, Navigation, and Control Center          |
| GOES  | Geostationary Operational Environmental Satellite |
| GPM   | Global Precipitation Mission                      |
| GPS   | Global Positioning Satellite                      |

|         |   |
|---------|---|
| GRO     | Gamma Ray Observatory                             |
| GSE     | Ground Support Equipment                          |
| GSFC    | Goddard Space Flight Center                       |
| GSRD    | Ground System Requirements Document               |
| GSRP    | Graduate Student Research Program                 |
| GTDS    | Goddard Trajectory Determination System           |
| GUS     | Gyroscopic Upper Stage                            |
| HD      | Henry Draper                                      |
| HDS     | Hybrid Dynamic Simulator                          |
| HEO     | High Earth Orbit/ Highly Elliptical Orbit         |
| HGA     | High Gain Antenna                                 |
| HTML    | HyperText Markup Language                         |
| ISEE-3  | International Sun-Earth Explorer 3                |
| I&T     | Integration and Test                              |
| ICD     | Interface Control Document                        |
| IHS     | Inner Heliospheric Sentinels                      |
| IM      | Ionosphere Mapper                                 |
| IMDC    | Integrated Mission Design Center                  |
| IMU     | Inertial Measurement Unit                         |
| ISU     | International Space University                    |
| ITAR    | International Traffic In Arms Regulation          |
| ITSO    | Information Technology Security Officer           |
| JPL     | Jet Propulsion Laboratory                         |
| LEO     | Low Earth Orbit                                   |
| LOR     | Launch and Orbit Raising                          |
| LPT     | Low Power Transceiver                             |
| LQG     | Linear Quadratic Gaussian                         |
| LRR     | Lightweight Rainfall Radiometer                   |
| MAP     | Microwave Anisotropy Probe                        |
| MARSAT  | Mars Areo-stationary Relay Satellite              |
| MC      | Master Catalog                                    |
| MCC     | Mid Course Correction                             |
| MCO     | Mars Climate Observer                             |
| MIT     | Massachusetts Institute of Technology             |
| MLS     | Microwave Limb Sounder                            |
| MMS     | Magnetic Multi-scale Mission                      |
| MOC     | Mission Operations Center                         |
| MOCC    | Mission Operations Command and Control            |
| MODIS   | Moderate Resolution Imaging Spectroradiometer     |
| MOPSS   | Mission Operations Planning and Scheduling System |
| MOST    | Mission Operations Support Team                   |
| MOWG    | Mission Operations Working Group                  |
| MSRD    | Mission Specific Requirements Document            |
| MU-SPIN | Minority University - Space Interdisciplinary     |
| NASA    | National Aeronautical and Space Administration    |
| NGST    | Next Generation Space Telescope                   |
| NMM     | Normal Maneuver Mode                              |
| NOAA    | National Oceanic and Atmospherics Administration  |
| NPB     | Navigation Processor Board                        |
| NPM     | Normal Pointing Mode                              |

|              |  |
|--------------|--|
| NRTS         | Network Resources and Training Sites   |
| NSF          | National Science Foundation  |
| NT           | New Technology   |
| OAT          | Orbit Adjust Thrusters   |
| ONS          | Onboard Navigation Systems   |
| OSSM         | Ocean Surface Salinity Mission   |
| PC           | Personal Computer  |
| PI           | Principal Investigator   |
| PICASSO-CENA | Pathfinder Instruments for Cloud and Aerosol Spaceborne Observations - Climatologie Etendue des Nuages et des Aerosols |
| PLT          | Post Launch Testing  |
| PREST        | Program of Research and Education in Space Technology  |
| QuikSCAT     | Quick Scatterometer  |
| R&D          | Research and Development   |
| RBM          | Radiation Belt Mapper  |
| RMS          | Root-Mean-Square   |
| RPO          | Radiation Protection Office  |
| RSDO         | Rapid Spacecraft Development Office  |
| RTOD         | Real-time Orbit Determination  |
| RWA          | Reaction Wheel Assembly  |
| RXTE         | Rossi X-Ray Timing Explorer  |
| SA           | Selective Availability   |
| SAMPEX       | Solar Anomalous and Magnetospheric Particle Explorer   |
| SMEX         | Small Explorer   |
| SOHO         | Solar and Heliospheric Observatory   |
| SOMO         | Space Operations Management Office   |
| SPECS        | Evolution of Cosmic Structure  |
| SPS          | Standard Positioning Service   |
| ST           | Space Technology   |
| TDRSS        | Tracking Data Relay Satellite System   |
| TMM          | Thruster Maneuver Mode   |
| TONS         | TDRSS Onboard Navigation System  |
| TRACE        | Transition Region and Coronal Explorer   |
| TRMM         | Tropical Rainfall Measuring Mission  |
| URL          | Uniform Resource Locator   |
| USN          | Universal Space Network  |
| VCM          | Velocity Control Mode  |
| VIIRS        | Visible Infrared Imaging Radiometer Suite  |
| WAAS         | Wide Area Augmentation System  |
| WIRE         | Wide-Field Infrared Explorer   |
| WISE         | Women in Science and Engineering   |
| WON          | Women of NASA  |
| WRS          | World Reference System   |
| WWW          | World Wide Web   |



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